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Development of criteria for automatic steering.

Spyromilios, Pericles Kyritsis

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THESIS

DEVELOPMENT OF CRITERIA FOR AUTOMATIC STEERING

By

Pericles Kyritsis-Spyromilios

December 1984

Thesis Advisor: G.J. Thaler

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effect of added resistance due to steering on a high-speed containership is propulsion reduction. Limitation on the propulsion losses can be achieved by a properly designed controller, which minimizes the rudder activity as well as providing desired overseas heading.

A computer program, simulating a cascade configuration of the SL-7 high-speed containership along with a specific

controller was coupled to a function minimization subroutine as well as a sea state generator subroutine in order to minimize a performance criterion.

The entire model was tested for a fixed speed, several encounter frequencies, several encounter angles in calm waters and in a seaway as well.

Development of Criteria for Automatic Steering

by

Pericles Kyritsis-Spyromilios
Lieutenant, Hellenic Navy
B.S., Naval Academy of Greece, 1975

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requirements for the degree of

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ABSTRACT

The effect of added resistance due to steering on a high-speed containership is propulsion reduction. Limitation on the propulsion losses can be achieved by a properly designed controller, which minimizes the rudder activity as well as providing desired overseas heading.

A computer program, simulating a cascade configuration of the SL-7 high-speed containership along with a specific controller was coupled to a function minimization subroutine as well as a sea state generator subroutine in order to minimize a performance criterion.

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I. INTRODUCTION

The 1973 oil crisis,where the price of a barrel of oil jumped higher than 210 percent and affected every aspect of the world economy,directly affected the shipping transportation industries.Whereas the price of oil was formerly of modest importance, it became a prime concern.Extensive association to the emerged problem has to do with the design of autopilots for ships, which can minimize propulsive losses caused by added resistance due to steering.

One motivation for the design of an optimum steering controller was the work done by Nomoto and Motoyama who claimed that reduction in propulsion loss could amount to a 1 percent savings in fuel consumption.

For most commercial ships a 1 to 2 percent saving in fuel costs,justifies the expense of fitting an autopilot which has the capability of producing this savings [Ref. 1].

Chapter 2 addresses what type of computer model can be used to represent the ship.Several of these models are investigated,such as simulation from the equations of motion and the Nomoto third order which was developed from the equation of motion.

Chapter 3 addresses the problem of selecting an adequate cost function to represent the added resistance due to steering.

The problem of finding the best controller design to provide a minimum value of added resistance due to steering, for regular and irregular seas,is studied in Chapters 4 and 5 respectively by using as a model of the ship the equations of motion and a function minimization subroutine.

Chapter 6 indicates how the controller parameters can be adjusted in any encounter environmental condition by means of an adaptive control.

Chapter 7 presents the conclusions from the experimental work.

II. DESCRIPTION OF COMPUTER MODELS

The most accurate model which can represent the ship/ steering dynamics is the model which is based upon the equations of motion as defined by series expansion including all terms (both linear and nonlinear).

Using experimentally measured hydrodynamic coefficients, for the SL-7 high speed containership, a computer program was developed in order to provide a computer simulation for the ship.Figure 2.1 shows the block diagram and the computer program can be found in Appendix A [Ref. 2,3].

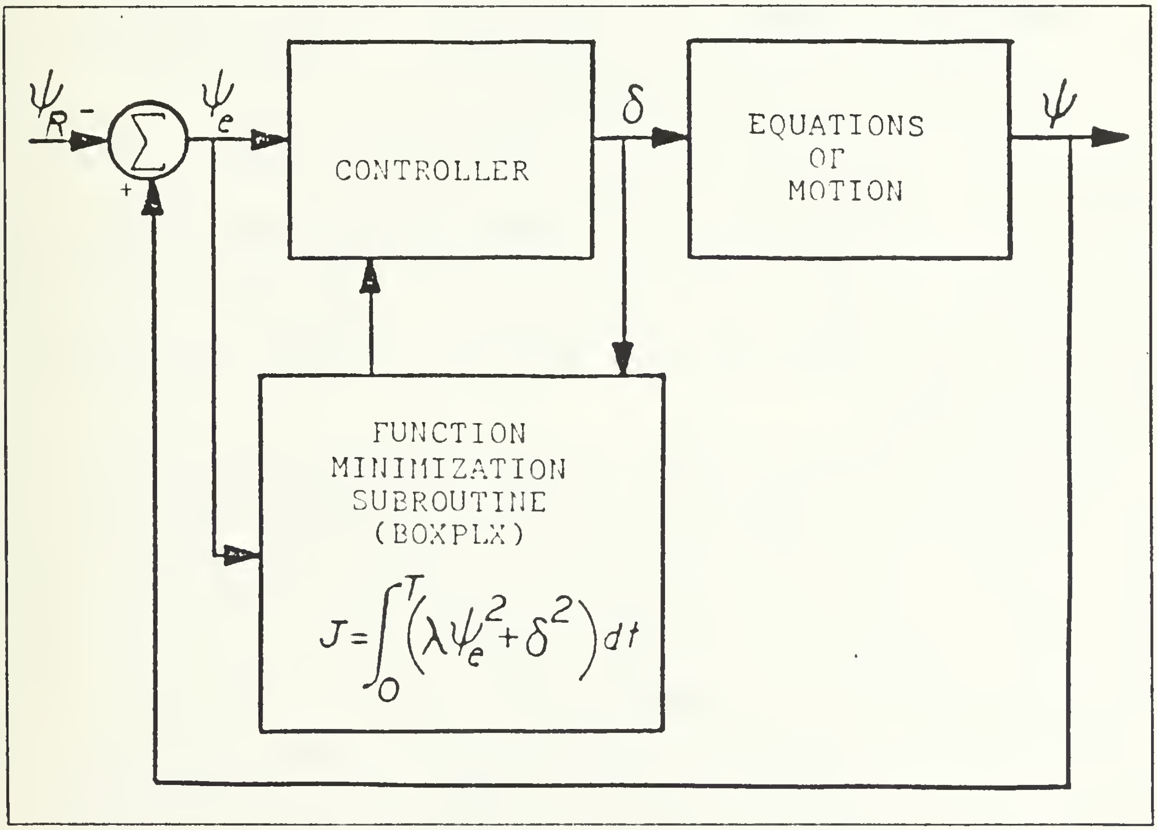

Figure 2.1 Block Diagram of Ship and Control System

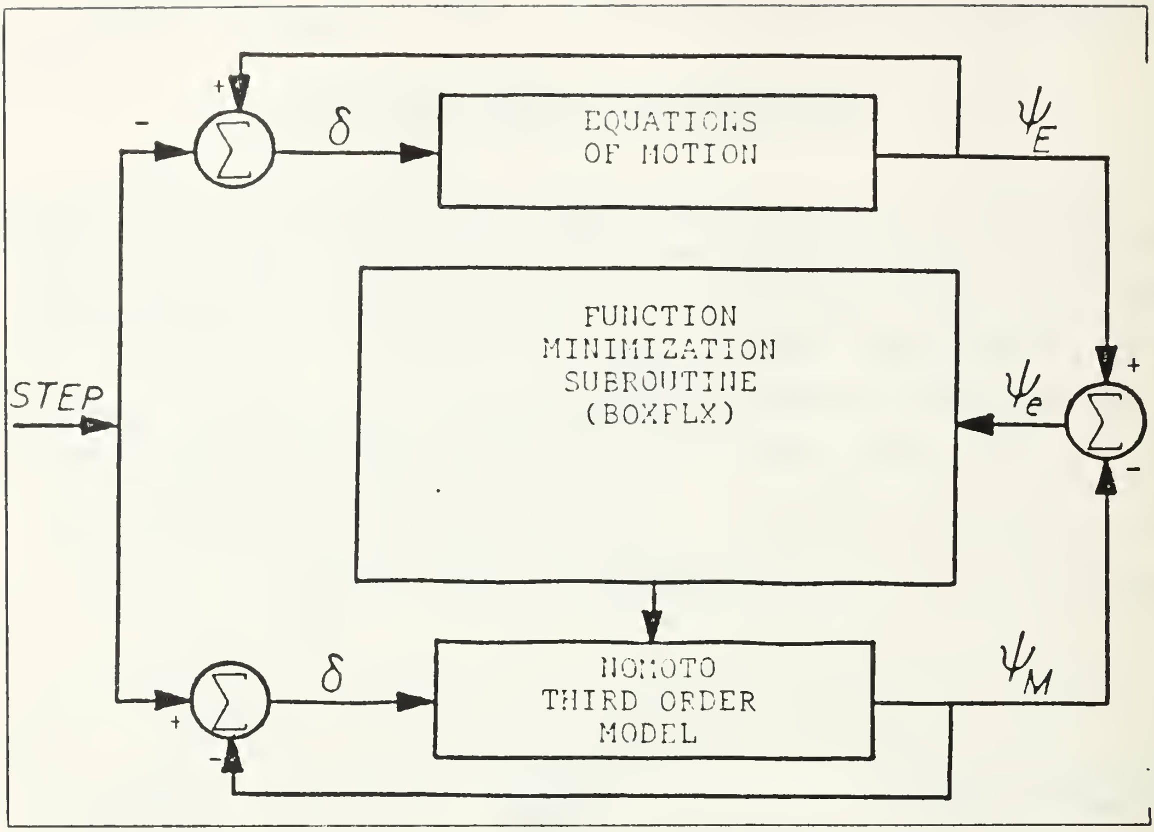

Figure 2.2 Determination of Nomoto Third Order Model

As a next choice, from the equations of motion we derive the Nomoto third order transfer function. Figure 2.2 shows the block diagram.

Using the scheme of Figure 2.2 which includes the function minimization subroutine with both yaw and sway equations, with the linear terms only we obtain the appropriate coefficients of the Nomoto third model. (Including in the equations of motion nonlinear terms we can see that the perturbations were small enough).

The function minimization subroutine used was BOXPLX, which was programed by R. Hilleary.The task of the already mentioned subroutine is to find the minimum of any function and is subjected to explicit constraints of the variables or

implicit constraints on functions of the variables.In addition it can handle a maximum of 25 variables [Ref. 4].

The extracted results were very close to the results we got by the analytic solution and are tabulated below only for 16, 23 and 32 knots.

TABLE 1

Nomoto Third Order Model

SPEED		MK		MZ		MP1		MP2	
KNOT	FT/SEC	CALC.	COMP.	CALC.	COMP.	CALC.	COMP.	CALC.	COMP.
16	27	0.0738	0.0738	22.567	22.567	12.945	12.945	107.58	107.583
23	38.81	0.1067	0.1053	15.675	15.199	9.014	8.696	75.13	73.893
32	54	0.1476	0.1477	11.29	11.283	6.5	6.469	53.76	53.793

III. STEERING PERFORMANCE CRITERION

Studying the literature, one can see many approaches to the problem of optimizing an automatic ship steering controller for maximum reduction in fuel consumption. Since added resistance is directly related to both rudder activity and yawing motion we can express a measure of this added resistance given as a performance criterion with the formula:

$$J = \frac{1}{T}\int_0^T \left(\lambda \psi_e^2 + \delta^2\right) dt \qquad (3.1)$$

Where:

- Delta (δ)=rudder angle
- Psi (ψ_e) =yaw angle
- Lambda(λ)=weighting factor

This formula defines an approximate drag due to steering for small amplitude oscillations about a steady-state pivot point of the ship during yawing at the natural frequency of the closed-loop ship/steering system.(About 0.05 rad/sec for the SL-7 containership).It is also convenient for shipboard use because yaw error and rudder angle can be easily measured.

During this study the values for the weighting factors are taken from R. E. Reid's work for the high-speed containership SL-7 [Ref. 5].

TABLE 2

Weighting Factors

Ship's Speed,Knots	Lambda
16	16.796
23	8.128
32	4.2

In Table 2 weighting factors for the operating range of the ship are tabulated.

IV. CONTROLLER DESIGN FOR REGULAR SEAS

Our goal now, is to estimate the system's performance in a seaway. To accomplish the above task first we must determine a suitable representation of the external disturbances on the ship by the sea. This can be done, since a sufficiently accurate computer ship model and a steering performance criterion have been defined.

It can be postulated that a sufficiently accurate model of the seaway itself, is a representative modeling of forces and moments exerted on the ship [Ref. 6,7,8]. An explanation of what a sea comprises, and how predicted or observed sea states can be analyzed to determine the forces and motions of a body in a sea was studied by Michael [Ref. 9].

In this chapter we will use as a seaway representation the regular sea model in which the forces on the ship [Ref. 10], have the form:

$$W_h \cdot R_e \cdot \cos\left(\omega_e t + \vartheta_i\right) \tag{4.1}$$

Where:

- R_e =exciting force
- ω_e =encounter frequency
- W_h =wave height
- ϑ_i =phase angle

Values for the exciting force ( ) for different encounter angles and different encounter frequencies as well, were taken from [Ref. 3]. Table 3 shows the correspondence between wave height and sea state which were used in this work.

The controller used in the present study is shown in Appendix B and its form is repeated here in Figure 4.1 .

TABLE 3

Sea State Vs Wave Height

Sea State (Beaufort scale)	Wave Height (in feet)
1	4.0
2	4.5
4	5.5
6	10.0
7	17.5

$$\longrightarrow \boxed{\frac{K_1(1+T_1S)\,(1+T_4S)}{(1+T_2S)\,(1+T_3S)}} \longrightarrow$$

Figure 4.1 Controller C

Values for the optimal gains for the above controller and values for the cost J as well, are shown below in Tables 4,5,6,7,8,9,10,11

These values were obtained using:

- Sea states 1-2-4-6-7 (Beaufort scale).
- Encounter angles 0°-30°-60°-90°.
- Encounter frequencies 0.2-0.4-0.6-0.75-1.5 rad per sec.
- Constant speed 23 knots.

A careful analysis of the extracted results lead us to conclude:

- The maximum deviation of controller parameter values occured at 0.4 rad per sec encounter frequency for all used encounter angles and sea states.
- For the same encounter frequency,for all encounter angles studied, the controller parameter values increasing smoothly as the sea state increases.
- For all encounter frequencies and for specific encounter angles, we observe that the cost increases at higher sea states.
- For 0.4 rad per sec encounter frequency the cost changes rapidly for sea state 6 and 7 as we move through the encounter angles.
- For the same encounter angles and sea states the cost decreases at higher encounter frequencies.
- For all encounter angles and encounter frequencies the maximum cost occured for sea state 7.
- The cost had it's maximum value for encounter angle 90° and encounter frequency 0.4 rad per sec.

Furthermore in order to obtain the behavior of the rudder and yaw motion of the ship, transient response plots were obtained for controller 'C' at ship's speed 23 knots, different sea states and encounter angles as shown in Figures 4.2 through 4.15

These plots were obtained using the program of Appendix C.

From these plots it is verified that for the same encounter frequencies and encounter angles, rudder and yaw motion increases in amplitude as the sea states rises.

Finally Figures 4.16,4.17,4.18,4.19,4.20, show the results of an experiment in which we were changing one controller parameter keeping the rest fixed, and we observed that the cost does not change significantly in the vicinity of the actual value.

Using that as a fact we can postulate that for a specific sailing mode for the controller parameter values high accuracy is not required.

Comparing controller C with controller A it is obvious that the parameter values of controller A vary over wider range.

TABLE 4

Controller C For 0° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	1	2
K1=	1.3999996	1.3999996
T1=	58.2299957	58.2299957
T2=	24.0000000	24.0000000
T3=	10.5000000	10.5000000
T4=	3.0000000	3.0000000
Cost J=	0.6382236E-33	0.8077518E-33

Encounter Frequency 0.4 Rads Per Sec

Sea State:	1	2
K1=	1.3999996	1.3999996
T1=	58.2299957	58.2299957
T2=	24.0000000	24.0000000
T3=	10.5000000	10.5000000
T4=	3.0000000	3.0000000
Cost J=	o.9306967E-35	0.1177913E-34

Encounter Frequency 0.6 Rads Per Sec

Sea State:	1	2
K1=	1.3999996	1.3999996
T1=	58.2299957	58.2299957
T2=	24.0000000	24.0000000
T3=	10.5000000	10.5000000
T4=	3.0000000	3.0000000
Cost J=	0.1868590E-36	0.2364934E-36

Encounter Frequency 0.75 Rads Per Sec

Sea State:	1	2
K1=	1.3999996	1.3999996
T1=	58.2299957	58.2299957
T2=	24.0000000	24.0000000
T3=	10.5000000	10.5000000
T4=	3.0000000	3.0000000
Cost J=	0.1917420E-38	0.2426735E-38

Encounter Frequency 1.5 Rads Per Sec

Sea State:	1	2
K1=	1.3999996	1.3999996
T1=	58.2299957	58.2299957
T2=	24.0000000	24.0000000
T3=	10.5000000	10.5000000
T4=	3.0000000	3.0000000
Cost J=	0.1476825E-38	0.1869107E-38

TABLE 5

Controller C For 30° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	1	2
K1=	1.7432022	1.7434111
T1=	35.1575165	35.0142517
T2=	22.0137024	22.0644684
T3=	13.5792084	13.7818375
T4=	22.0728760	22.1337128
Cost J=	0.594662E+00	0.7502608E+00

Encounter Frequency 0.4 Rads Per Sec

Sea State:	1	2
K1=	0.2120571	0.1997837
T1=	92.9998932	99.9923096
T2=	24.2121429	24.2589569
T3=	39.9739990	39.9999542
T4=	32.8156433	34.0418396
Cost J=	0.2301481E-02	0.2901770E-02

Encounter Frequency 0.6 Rads Per Sec

Sea State:	1	2
K1=	1.8069019	1.7886524
T1=	1.1657065	1.1832294
T2=	12.4824829	13.3286743
T3=	13.7605896	15.5890350
T4=	9.2525921	9.2333460
Cost J=	0.1797669E-02	0.2275771E-02

Encounter Frequency 0.75 Rads Per Sec.

Sea State:	1	2
K1=	2.2712851	2.2712851
T1=	0.8431141	0.8431141
T2=	24.1657867	24.1657867
T3=	22.2913666	22.2913666
T4=	9.8764191	9.8764191
Cost J=	0.1094168E-02	0.1384705E-02

Encounter Frequency 1.5 Rads Per Sec

Sea State:	1	2
K1=	1.6945763	1.6945763
T1=	0.2571034	0.2571034
T2=	25.3036194	25.3036194
T3=	25.4920502	25.4920502
T4=	26.4106903	26.4106903
Cost J=	0.5423090E-04	0.6863636E-04

TABLE 6

Controller C For 60⁰ Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	1	2
K1=	2.1659079	2.1752367
T1=	29.1530609	28.9752655
T2=	18.6070404	18.4342346
T3=	10.7567606	10.5662384
T4=	18.3101044	18.4618378
Cost J=	0.7797163E=00	0.9817770E+00

Encounter Frequency 0.4 Rads Per Sec

Sea State:	1	2
K1=	0.8408279	0.8623953
T1=	73.1355896	74.4368439
T2=	53.1565094	57.8289948
T3=	22.6398926	24.3586884
T4=	49.9999390	49.9900360
Cost J=	0.7811032E+000.9783571E+00	

Encounter Frequency 0.6 Rads Per Sec

Sea State:	1	2
K1=	1.0592918	0.9676542
T1=	0.1000010	0.1343303
T2=	19.7355957	25.3748169
T4=	49.9999390	33.4176483
Cost J=	0.2017351E-02	0.2553086E-02

Encounter Frequency 0.75 Rads Per Sec

Sea State:	1	2
K1=	2.2673655	2.2673655
T1=	0.8431506	0.8431506
T2=	14.1734161	14.1734161
T3=	11.3151855	11.3151855
T4=	15.1259995	15.1259995
Cost J=	0.2704291E-02	0.3422481E-02

Encounter Frequency 1.5 Rads Per Sec

Sea State:	1	2
K1=	2.3734770	2.3808193
T1=	0.5810375	0.5764611
T2=	8.2907715	7.0220699
T3=	6.7814789	5.6438484
T4=	7.9672575	9.3380499
Cost J=	0.1145959E-02	0.1450353E-02

TABLE 7

Controller C For 90° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	1	2
K1=	1.3473454	1.3487740
T1=	35.3837585	35.2085876
T2=	19.5286560	19.5352631
T3=	15.7849731	15.8424835
T4=	19.3971252	19.5299683
Cost J=	0.1756000E+01	0.2201721E+01

Encounter Frequency 0.4 Rads Per Sec

Sea State:	1	2
K1=	1.6298742	1.6293240
T1=	31.0220642	31.2911530
T2=	18.8860321	19.0679169
T3=	12.3363419	12.2226353
T4=	18.8753967	19.0280762
Cost J=	0.6726980E+00	0.8399093E+00

Encounter Frequency 0.6 Rads Per Sec

Sea State:	1	2
K1=	1.9138527	1.9098577
T1=	1.1895151	1.1946430
T2=	10.0705585	10.1293569
T3=	11.7410755	11.8040771
T4=	10.0737257	10.1994019
Cost J=	0.5086016E-01	0.6385970E-01

Encounter Frequency 0.75 Rads Per Sec

Sea State:	1	2
K1=	1.8993120	1.8893242
T1=	0.4503812	0.4850104
T2=	27.3063202	31.5392303
T3=	21.9325409	27.4768982
T4=	28.9246674	26.0999603
Cost J=	0.2837797E-01	0.3586013E-01

Encounter Frequency 1.5 Rads Per Sec

Sea State		
K1=	2.4287634	2.4257565
T1=	0.6342447	0.6373515
T2=	7.4652443	7.9898472
T3=	5.9140081	6.1980715
T4=	5.8591156	5.1957550
Cost J=	0.1057035E-01	0.1336560E-01

TABLE 8

Controller C For 0° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	4	6	7
K1=	1.3999996	1.3999996	1.3999996
T1=	58.2299957	58.2299957	58.2299957
T2=	24.0000000	24.0000000	24.0000000
T3=	10.5000000	10.5000000	10.5000000
T4=	3.0000000	3.0000000	3.0000000
COST J=	0.9972246E-33	0.3988896E-32	0.1221600E-31

Encounter Frequency 0.4 Rads Per Sec

Sea State:	4	6	7
K1=	1.3999996	1.3999996	1.3999996
T1=	58.2299957	58.2299957	58.2299957
T2=	24.0000000	24.0000000	24.0000000
T3=	10.5000000	10.5000000	10.5000000
T4=	3.0000000	3.0000000	3.0000000
COST J=	0.1454213E-34	0.5816855E-34	0.1781412E-33

Encounter Frequency 0.6 Rads Per Sec

Sea State:	4	6	7
K1=	1.3999996	1.3999996	1.3999996
T1=	58.2299957	58.2299957	58.2299957
T2=	24.0000000	24.0000000	24.0000000
T3=	10.5000000	10.5000000	10.5000000
T4=	3.0000000	3.0000000	3.0000000
COST J=	0.2919672E-36	0.1167868E-35	0.3576599E-35

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	1.3999996	1.3999996	1.3999996
T1=	58.2299957	58.2299957	58.2299957
T2=	24.0000000	24.0000000	24.0000000
T3=	10.5000000	10.5000000	10.5000000
T4=	3.0000000	3.0000000	3.0000000
COST J=	0.2995968E-38	0.1198388E-37	0.3670063E-37

Encounter Frequency 1.5 Rads Per Sec

Sea State:	4	6	7
K1=	1.3999996	1.3999996	1.3999996
T1=	58.2299957	58.2299957	58.2299957
T2=	24.0000000	24.0000000	24.0000000
T3=	10.5000000	10.5000000	10.5000000
T4=	3.0000000	3.0000000	3.0000000
COST J=	0.2307540E-38	0.9230160E-38	0.2826737E-37

TABLE 9

Controller C For 30° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	4	6	7
K1=	1.7466650	1.7746067	1.8194151
T1=	35.2978973	36.3333435	48.3066101
T2=	22.2485657	23.2952423	45.8587494
T3=	13.6511078	13.4007721	25.3368378
T4=	22.1172638	23.5081635	23.1087189
COST J=	0.9229971E+00	0.3496342E+01	0.9325538E+01

Encounter Frequency 0.4 Rads Per Sec

Sea State:	4	6	7
K1=	0.2102537	0.2002187	0.2060161
T1=	92.8943787	99.9424896	95.9424133
T2=	23.9096680	24.3453674	24.2843170
T3=	39.9628601	39.9452667	38.9973450
T4=	33.1146698	33.9409027	33.4644012
COST J=	0.3595694E-02	0.1431070E-01	0.4376912E-01

Encounter Frequency 0.6 Rads Per Sec

Sea State:	4	6	7
K1=	1.8260603	1.8175459	1.8287125
T1=	1.1601276	1.1572495	1.1652012
T2=	11.2977753	10.3958378	10.5659571
T3=	12.5801849	11.7078133	11.7124157
T4=	10.2739115	10.7313347	10.5683947
COST J=	0.2808505E-02	0.1122463E-01	0.3429835E-01

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	2.2723074	2.3248615	2.3073282
T1=	0.8993683	0.8716087	0.8750648
T2=	22.2714996	13.4890442	13.0364380
T3=	20.4913177	10.3330994	10.1076660
T4=	10.0878286	12.5009842	13.1554108
COST J=	0.1709419E-02	0.6832119E-02	0.2090112E-01

Encounter Frequency 1.5 Rads Per Sec

Sea State:	4	6	7
K1=	1.9173651	1.8726044	1.6678009
T1=	0.6582609	0.3396787	0.3818831
T2=	38.7910156	31.8340454	27.1428680
T3=	19.3868103	29.9999695	26.3686218
T4=	17.9940795	24.4667816	27.3681793
COST J=	0.8474453E-04	0.3389677E-03	0.1038366E-02

TABLE 10

Controller C For 60° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	4	6	7
K1=	2.1778851	2.2266541	2.2981157
T1=	29.6119080	31.9857025	35.2284546
T2=	18.7636871	19.4135590	24.2031403
T3=	10.2442350	7.8426695	8.8281393
T4=	18.3449402	19.8131866	24.7627716
COST J=	0.1205183E+01	0.4414552E+01	0.1080894E+02

Encounter Frequency 0.4 Rads Per Sec

Sea State:	4	6	7
K1=	0.8723865	1.3212109	1.7475338
T1=	77.6901245	1.1219873	0.9073439
T2=	57.4288635	14.2327118	18.7083435
T3=	21.6142426	35.2742767	29.6310730
T4=	58.1057587	14.2909546	20.4921570
COST J=	0.1194492E+01	0.3620569E+01	0.1005195E+02

Encounter Frequency 0.6 Rads Per Sec

Sea State:	4	6	7
K1=	0.9356804	1.0065041	0.9630518
T1=	0.2035089	0.1434612	0.1086842
T2=	25.2695007	28.2131348	24.0041809
T3=	18.3522491	16.1927643	17.7048645
T4=	39.1636200	29.4095917	38.1658936
COST J=	0.3151959E-02	0.1260864E-01	0.3862068E-01

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	2.2310591	2.2579184	2.2688522
T1=	0.8066239	0.7918448	0.7898693
T2=	18.4929504	14.8840103	14.6062164
T3=	16.4596100	12.1710510	11.3906097
T4=	12.6112747	14.9709930	14.7650146
COST J=	0.4225172E-02	0.1688830E-01	0.5162057E-01

Encounter Frequency 1.5 Rads Per Sec

Sea State:	4	6	7
K1=	2.3292980	2.3723307	2.3858051
T1=	0.5873335	0.5848479	0.6092799
T2=	21.2806244	8.7543087	8.3835888
T3=	20.8198700	7.1684380	6.6424551
T4=	5.3823652	7.0838490	7.5094414
COST J=	0.1791609E-02	0.7157017E-02	0.2188155E-01

TABLE 11

Controller C For 90° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

Sea State:	4	6	7
K1=	1.3517475	1.3857212	1.4623213
T1=	35.3476257	36.2312164	42.9548187
T2=	19.6020966	21.4780426	28.4767914
T3=	15.6134491	15.0542984	14.1265106
T4=	19.6564178	21.3916779	28.5155182
COST J=	0.2690107E+01	0.9237458E+01	0.2028659E+02

Encounter Frequency 0.4 Rads Per Sec

Sea State:	4	6	7
K1=	1.0069885	1.1330795	1.1926146
T1=	49.7900391	3.6114454	0.7214398
T2=	36.0238495	18.1521301	37.0983887
T3=	15.7164612	31.1608582	39.9669037
T4=	35.5061340	17.9342651	38.7577972
COST J=	0.8278778E+01	0.1712465E+02	0.2298665E+02

Encounter Frequency 0.6 Rads Per Sec

Sea state:	4	6	7
K1=	1.8570919	1.9276266	1.8934374
T1=	1.0337286	0.9287271	0.4949190
T2=	11.9529600	15.0574036	30.3212738
T3=	12.3197098	13.4190674	27.2785339
T4=	11.7377634	15.0851593	26.5594635
COST J=	0.9655529E-01	0.2932869E+00	0.5224001E+00

Encounter Frequency 0.75 Rads Per Sec

Sea state:	4	6	7
K1=	1.9137421	1.8589468	1.7544203
T1=	0.4686716	0.3916095	0.1022463
T2=	26.6723328	32.9264069	42.4169006
T3=	20.3362122	27.4372711	29.9568634
T4=	30.0011749	32.4602356	52.5700073
COST J=	0.4419509E-01	0.1722615E+00	0.4958326E+00

Encounter Frequency 1.5 Rads Per Sec

Sea State:	4	6	7
K1=	2.3951197	2.4414005	2.4639597
T1=	0.6277218	0.6339726	0.6183524
T2=	4.0210686	6.7097816	7.3951139
T3=	6.0798759	4.9043417	5.1939421
T4=	69.4311066	6.7554045	7.3074417
COST J=	0.1650761E-01	0.6472868E-01	0.1906425E+00

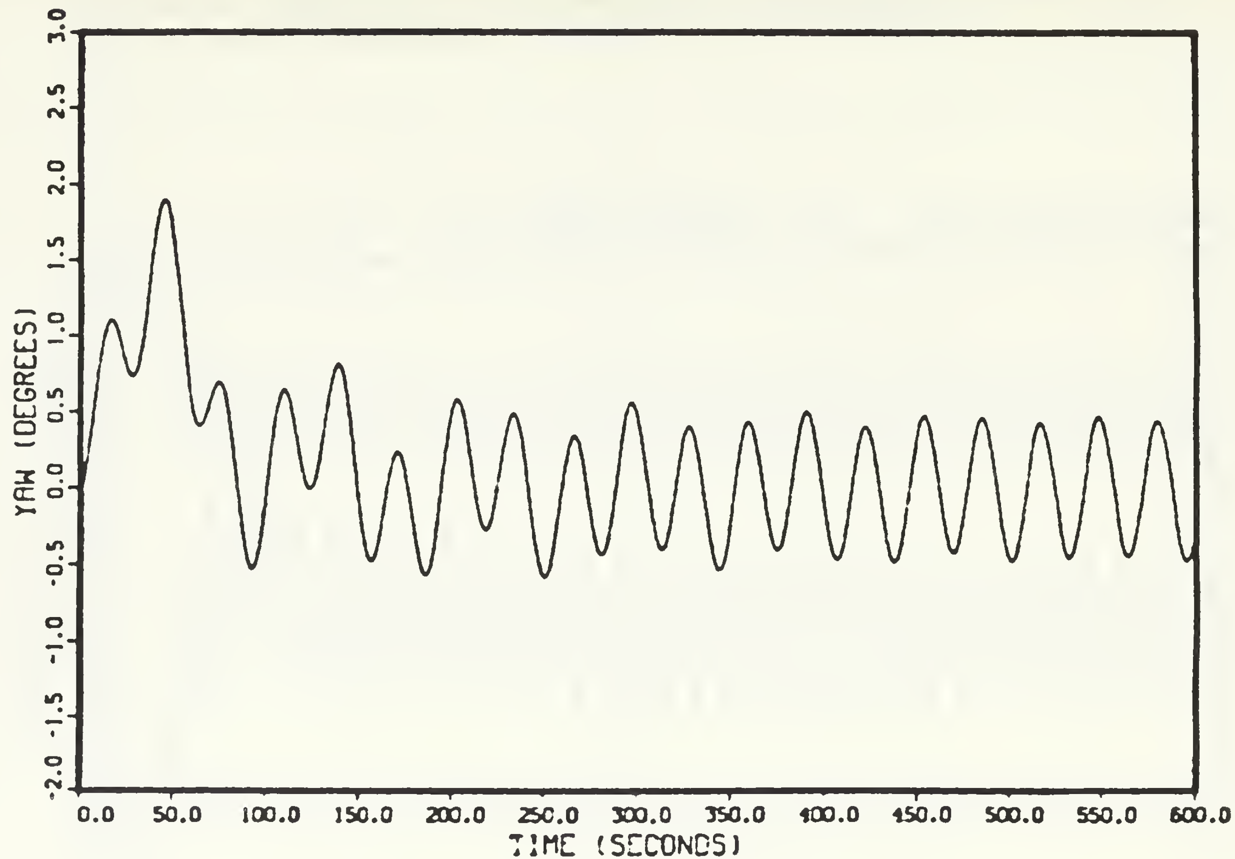

Figure 4.2 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

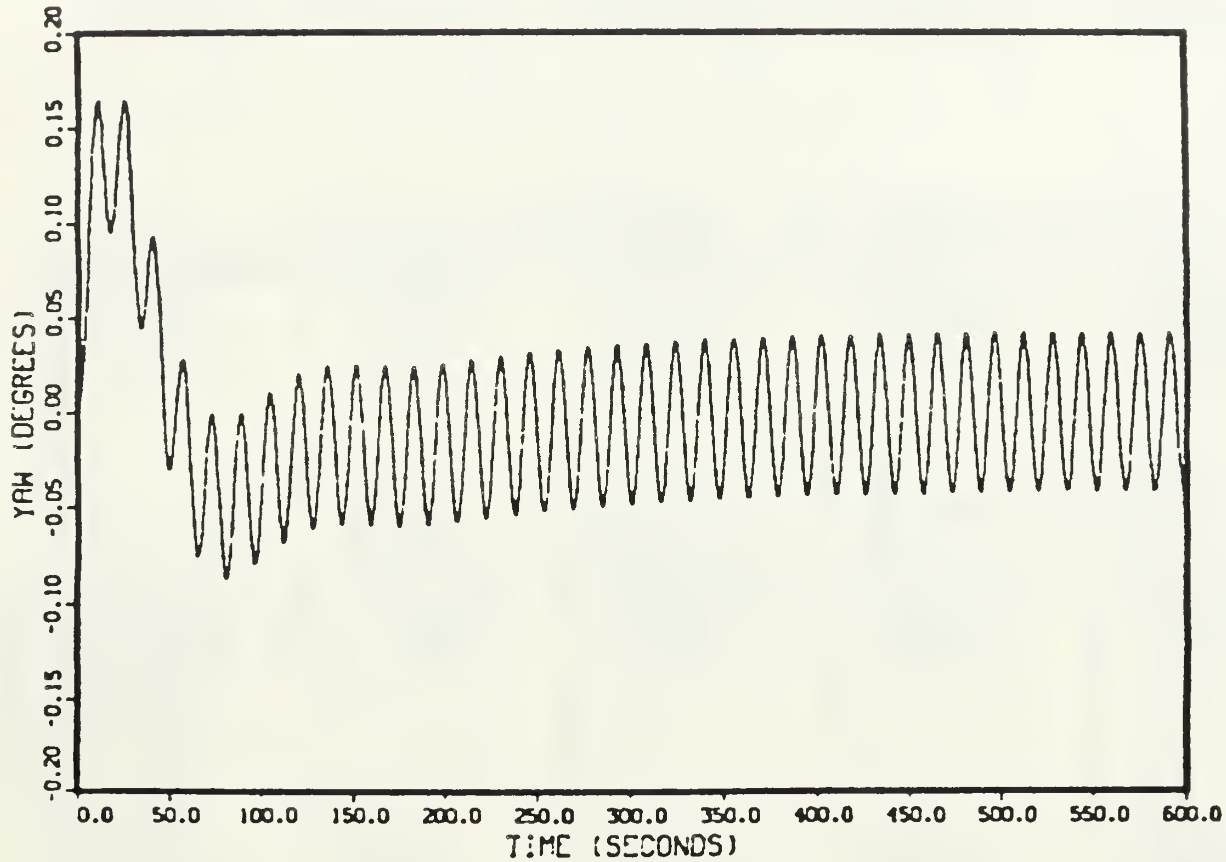

Figure 4.3 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.4 rads per sec,Encounter Angle 30°

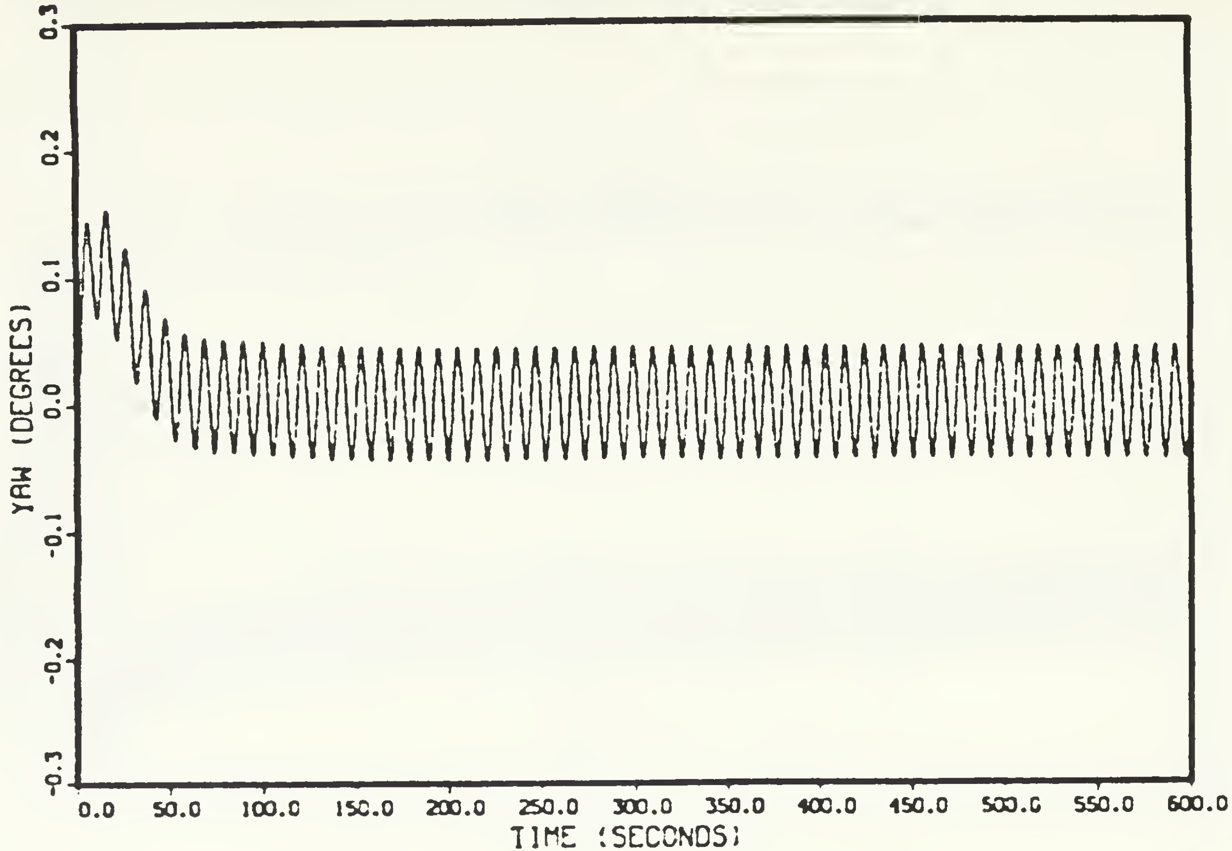

Figure 4.4 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.6 rads per sec, Encounter Angle 30°

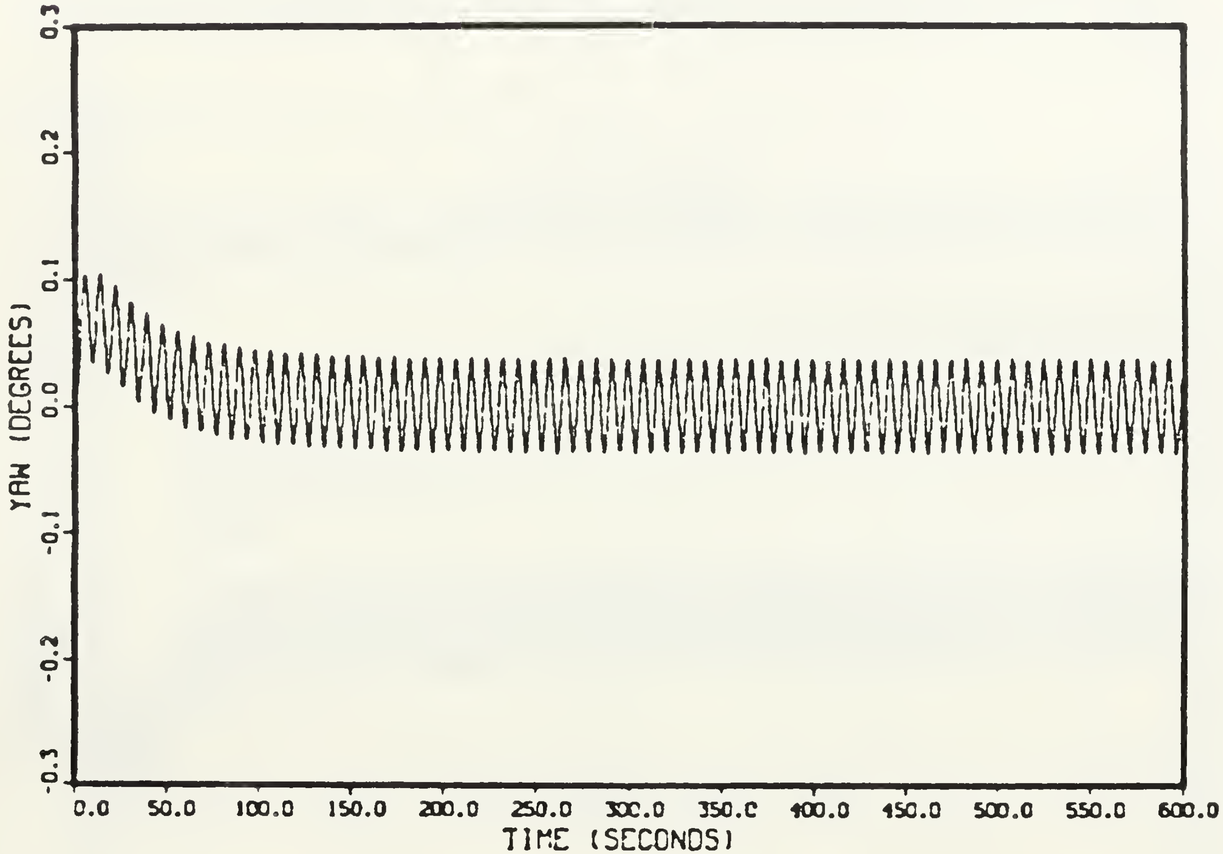

Figure 4.5 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.75 rads per sec, Encounter Angle 30°

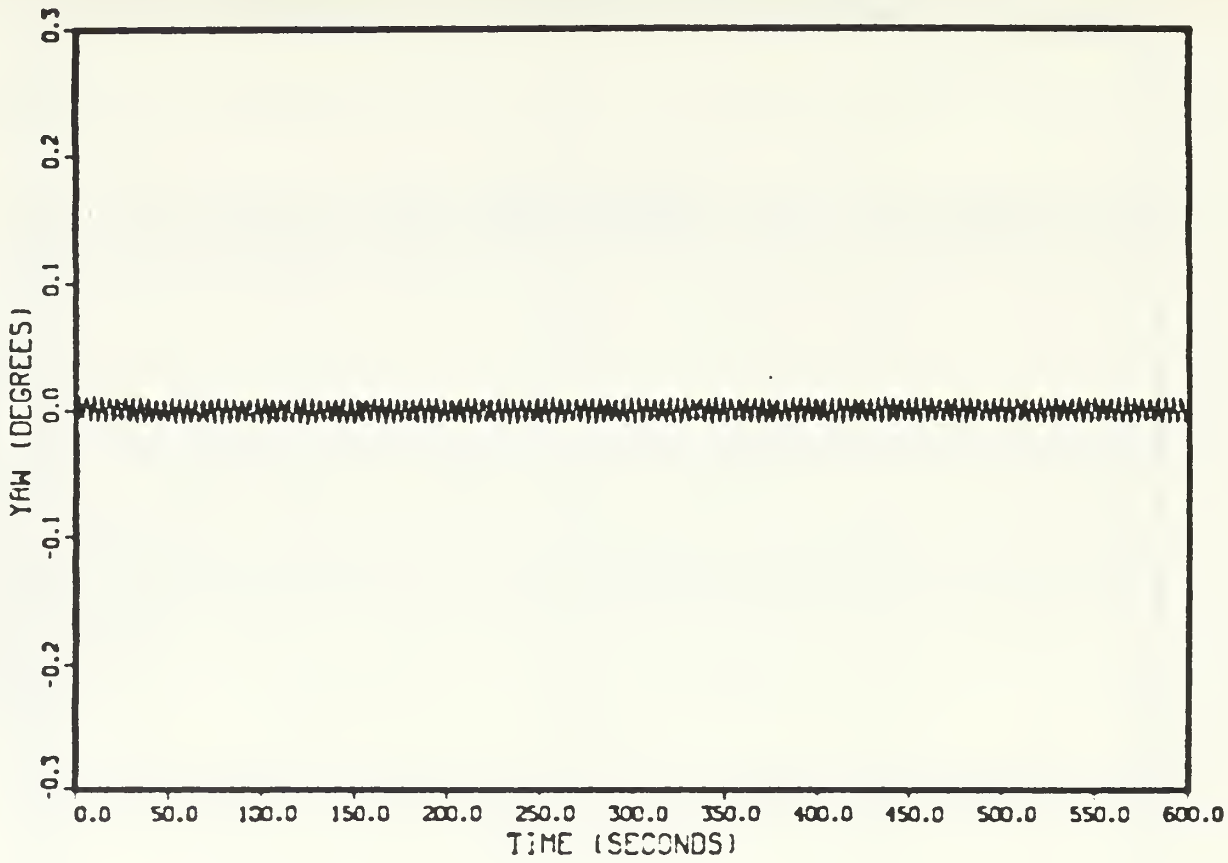

Figure 4.6 Yaw Vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 30°

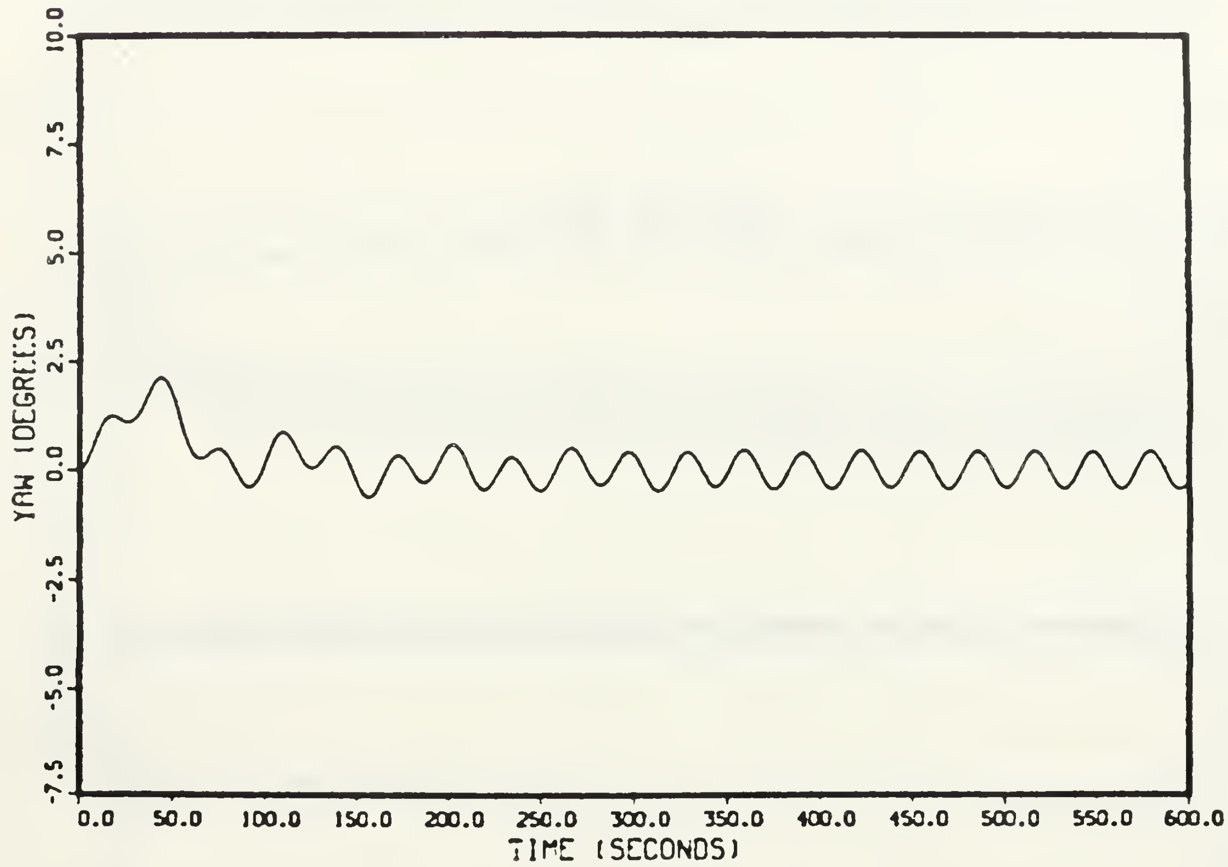

Figure 4.7 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 60°

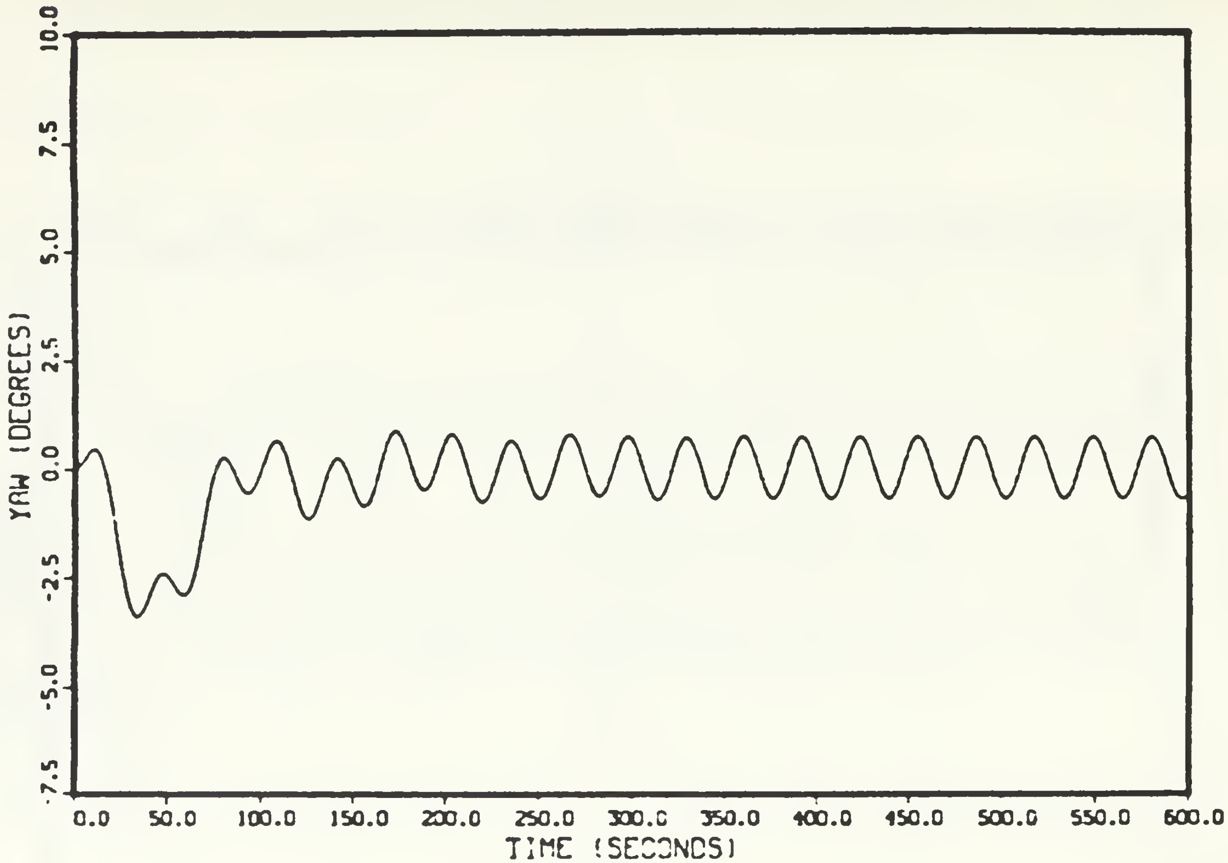

Figure 4.8 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 90°

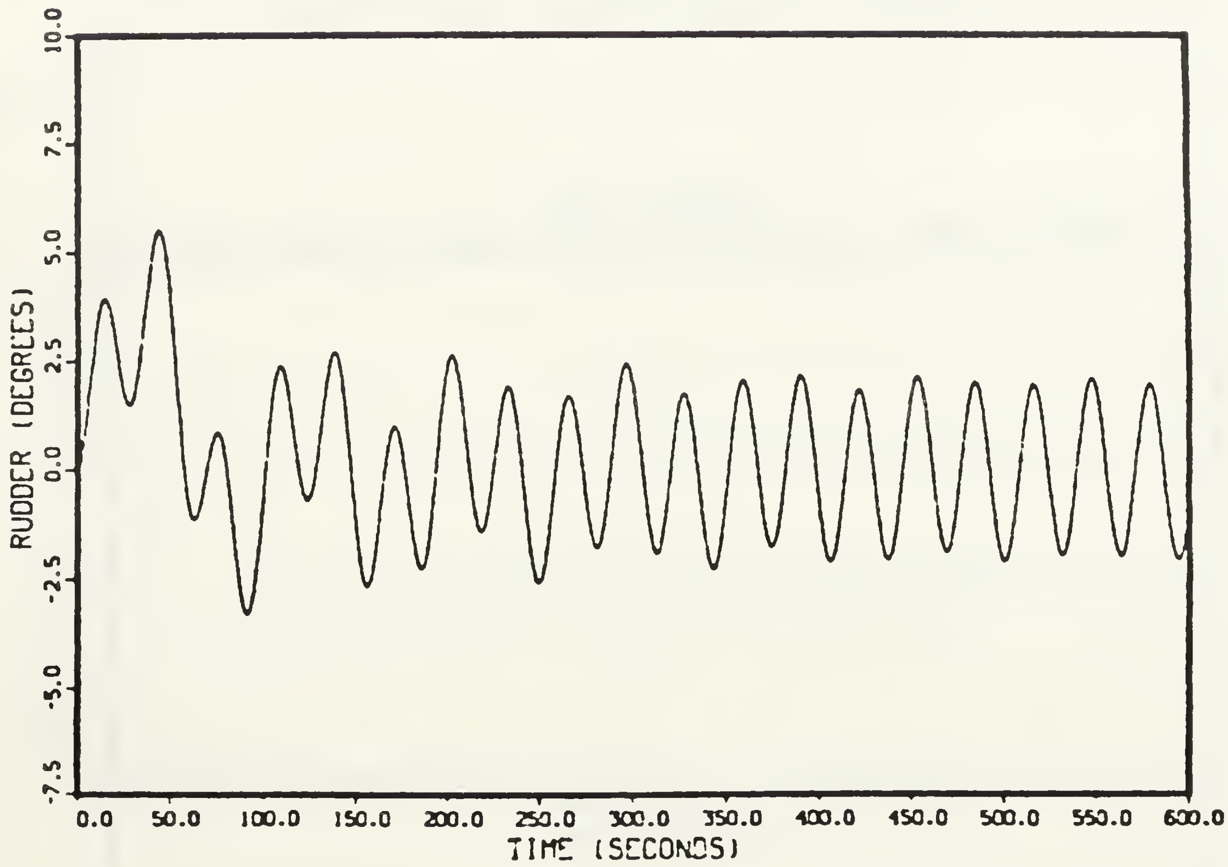

Figure 4.9 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

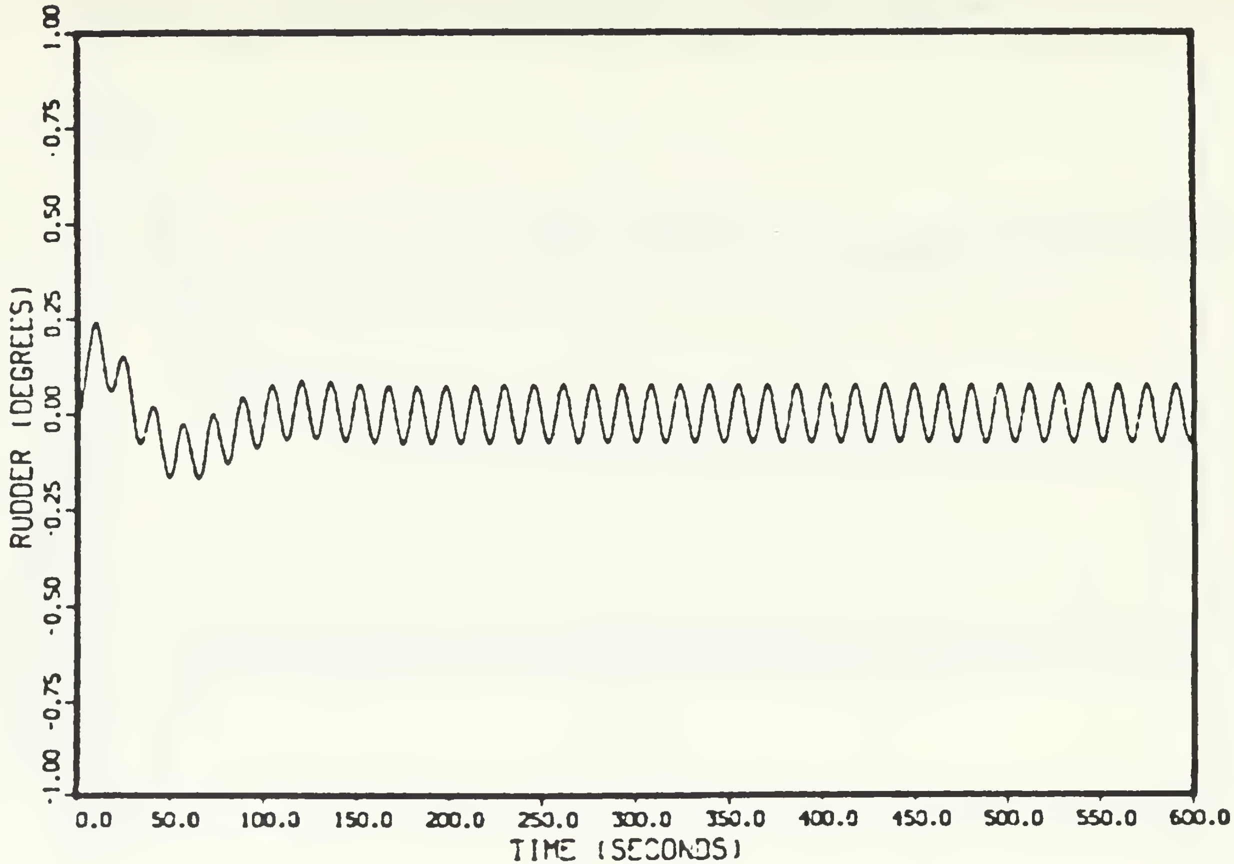

Figure 4.10 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.4 rads per sec, Encounter Angle 30°

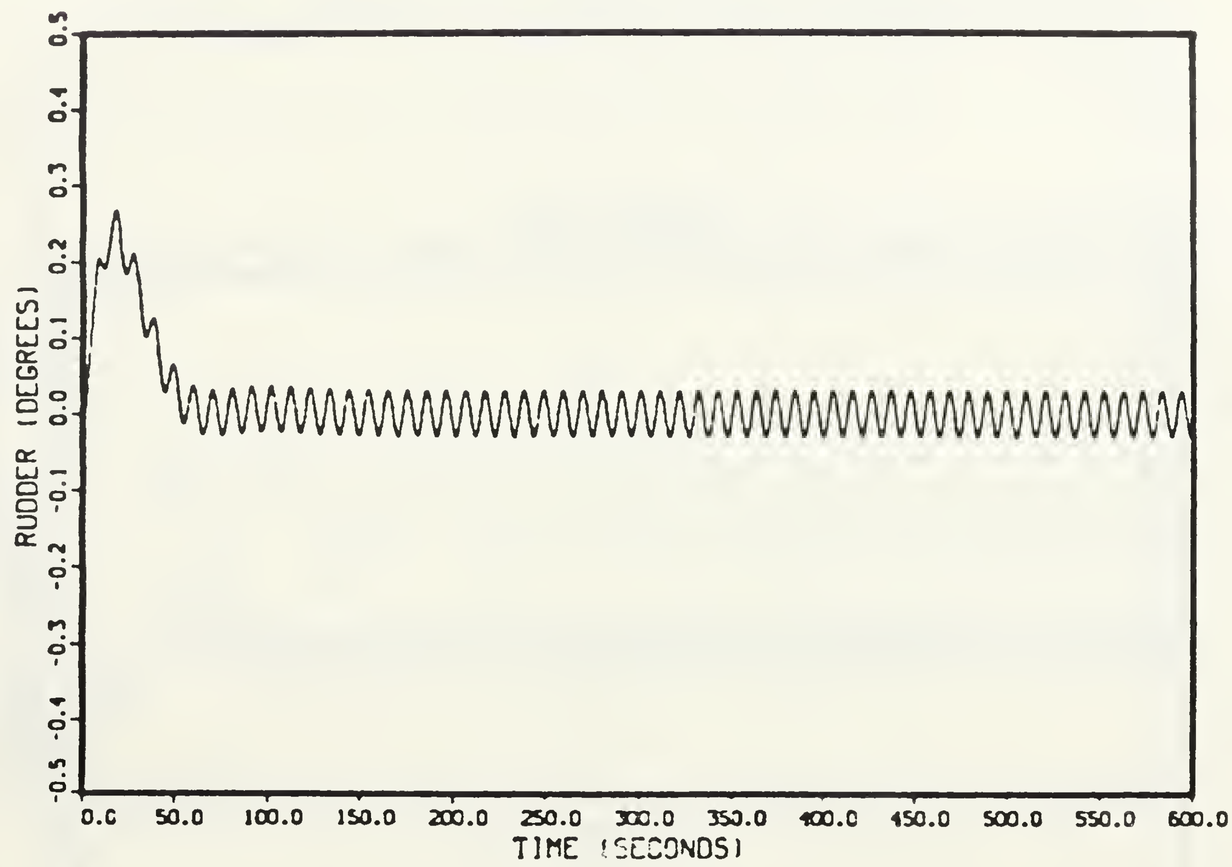

Figure 4.11 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.6 rads per sec, Encounter Angle 30°

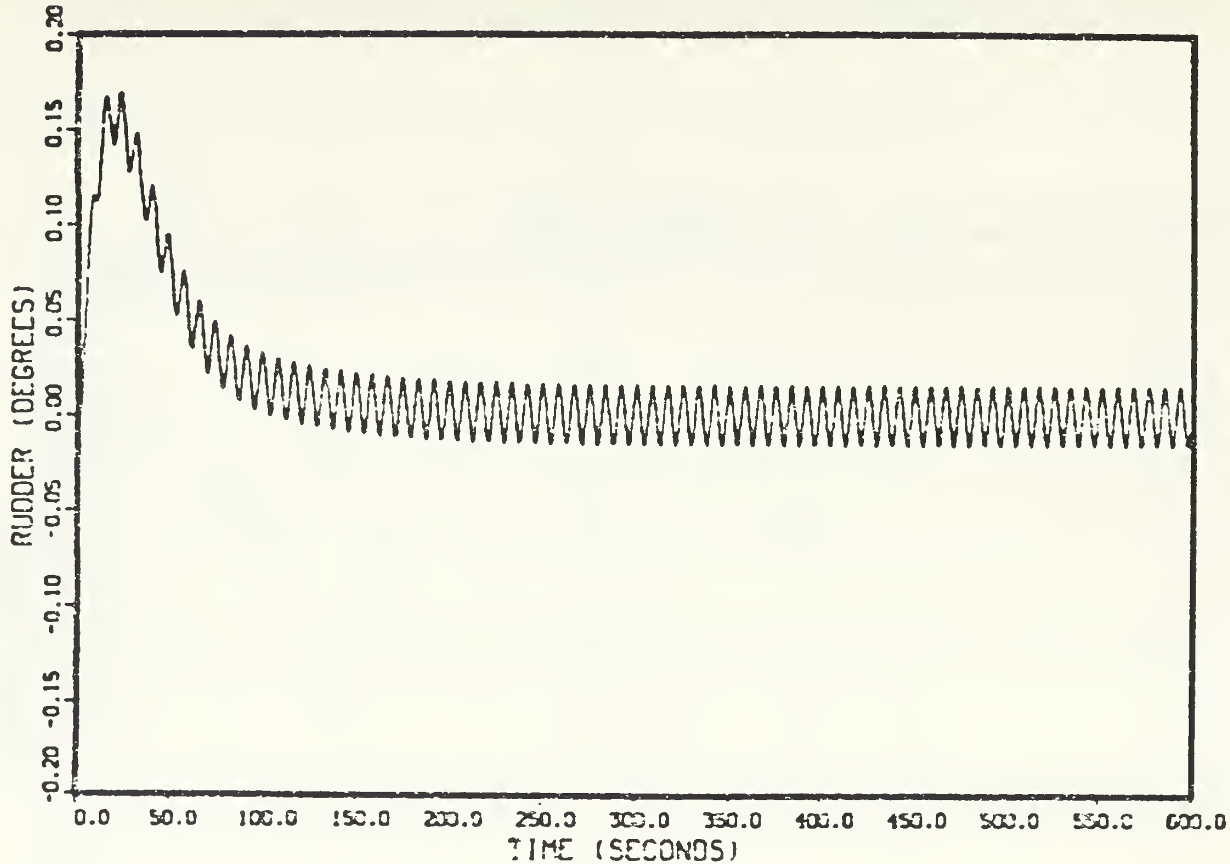

Figure 4.12 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.75 rads per sec, Encounter Angle 30°

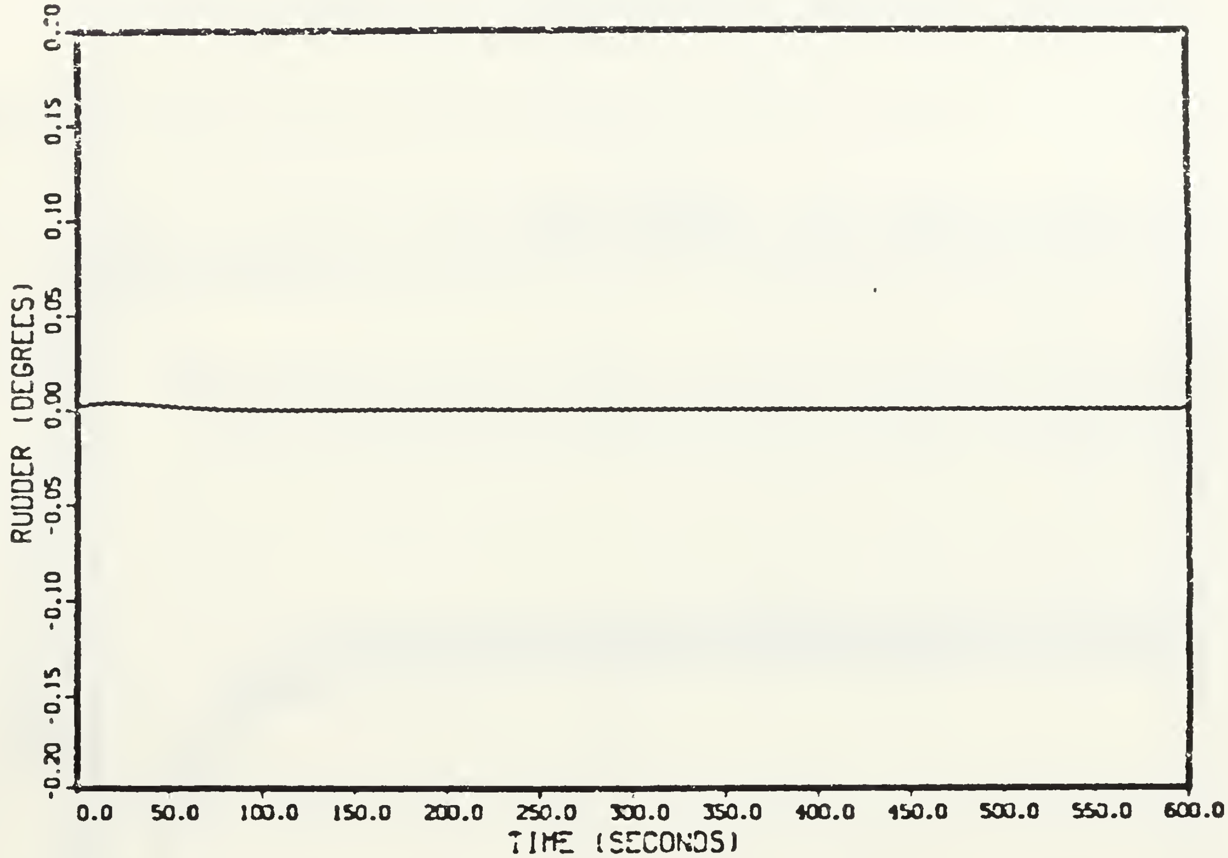

Figure 4.13 Rudder Vs Time, Sea State 4. Encounter Frequency 1.5 rads per sec, Encounter Angle 30°

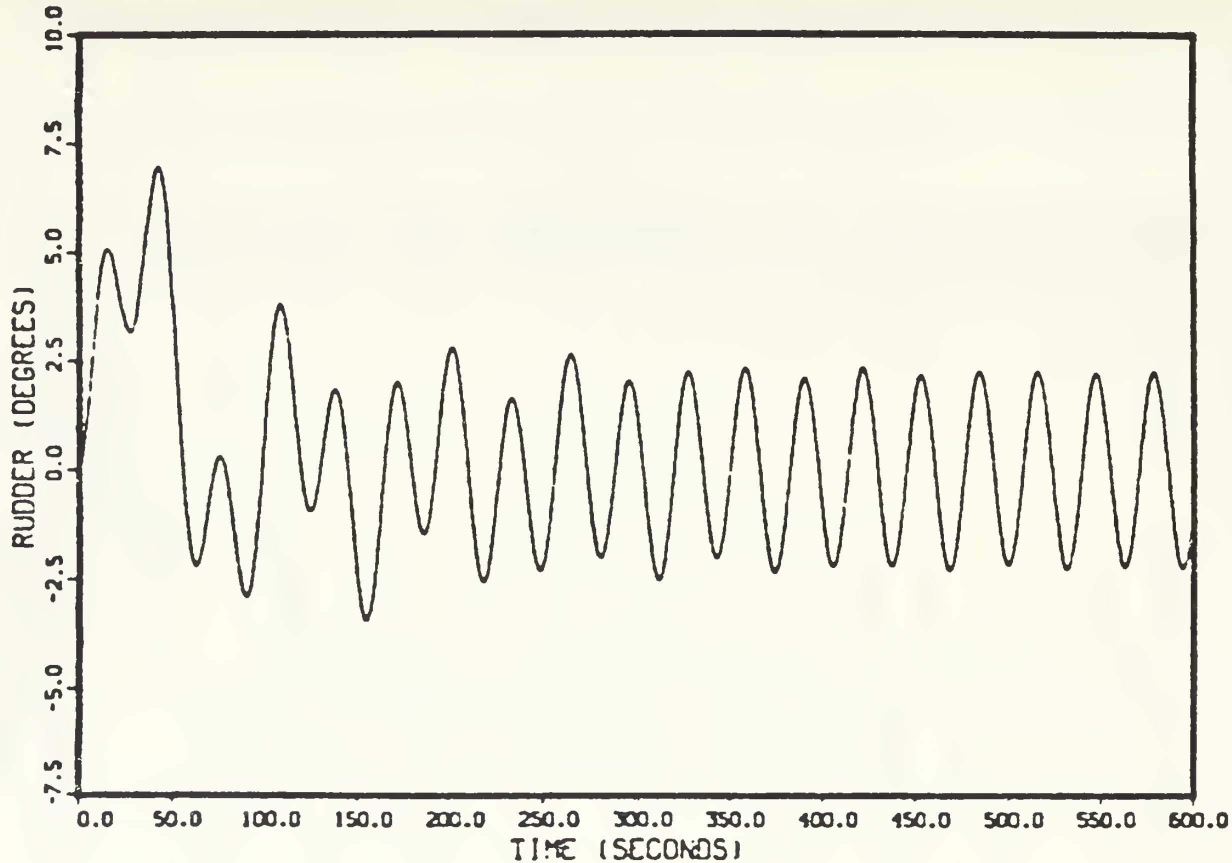

Figure 4.14 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 60°

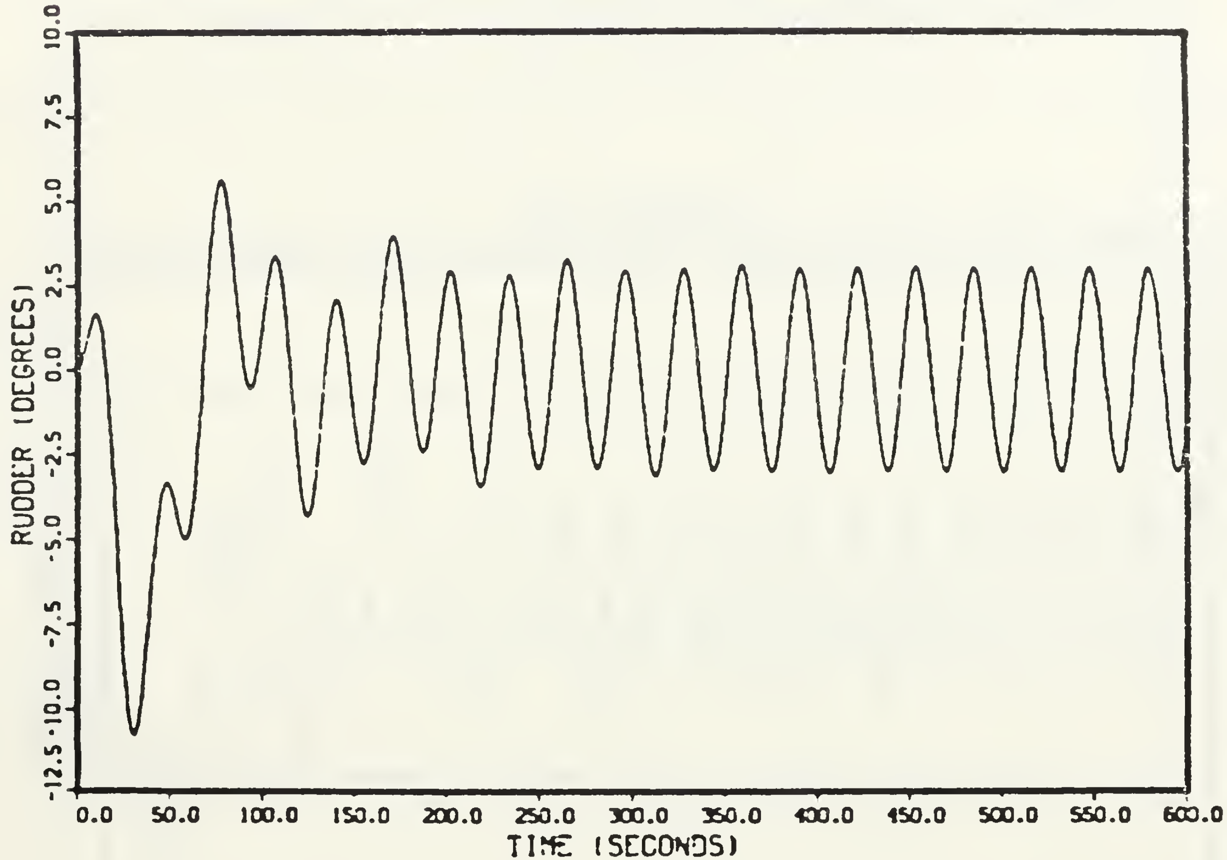

Figure 4.15 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 90°

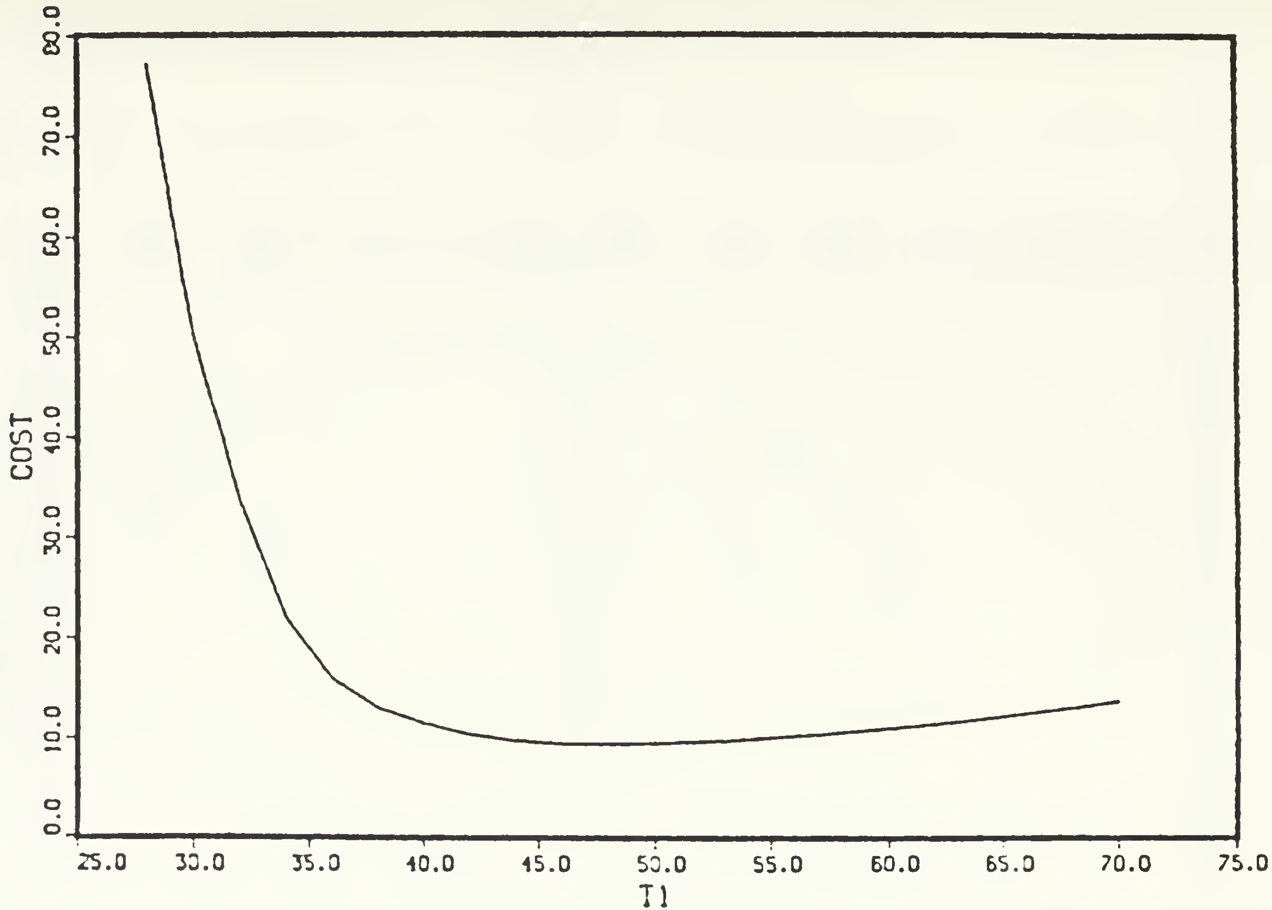

Figure 4.16 Cost Vs T1, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

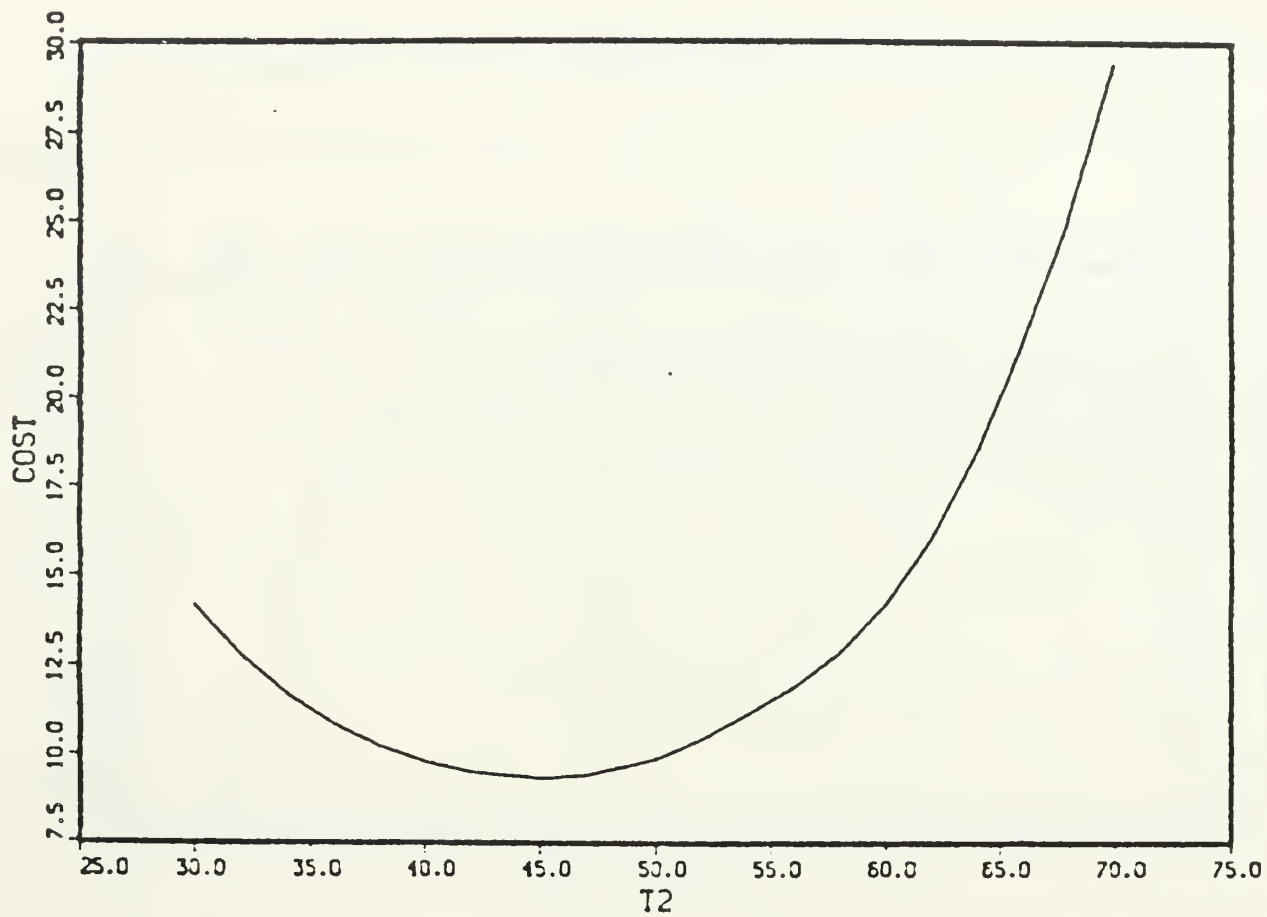

Figure 4.17 Cost Vs T2, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

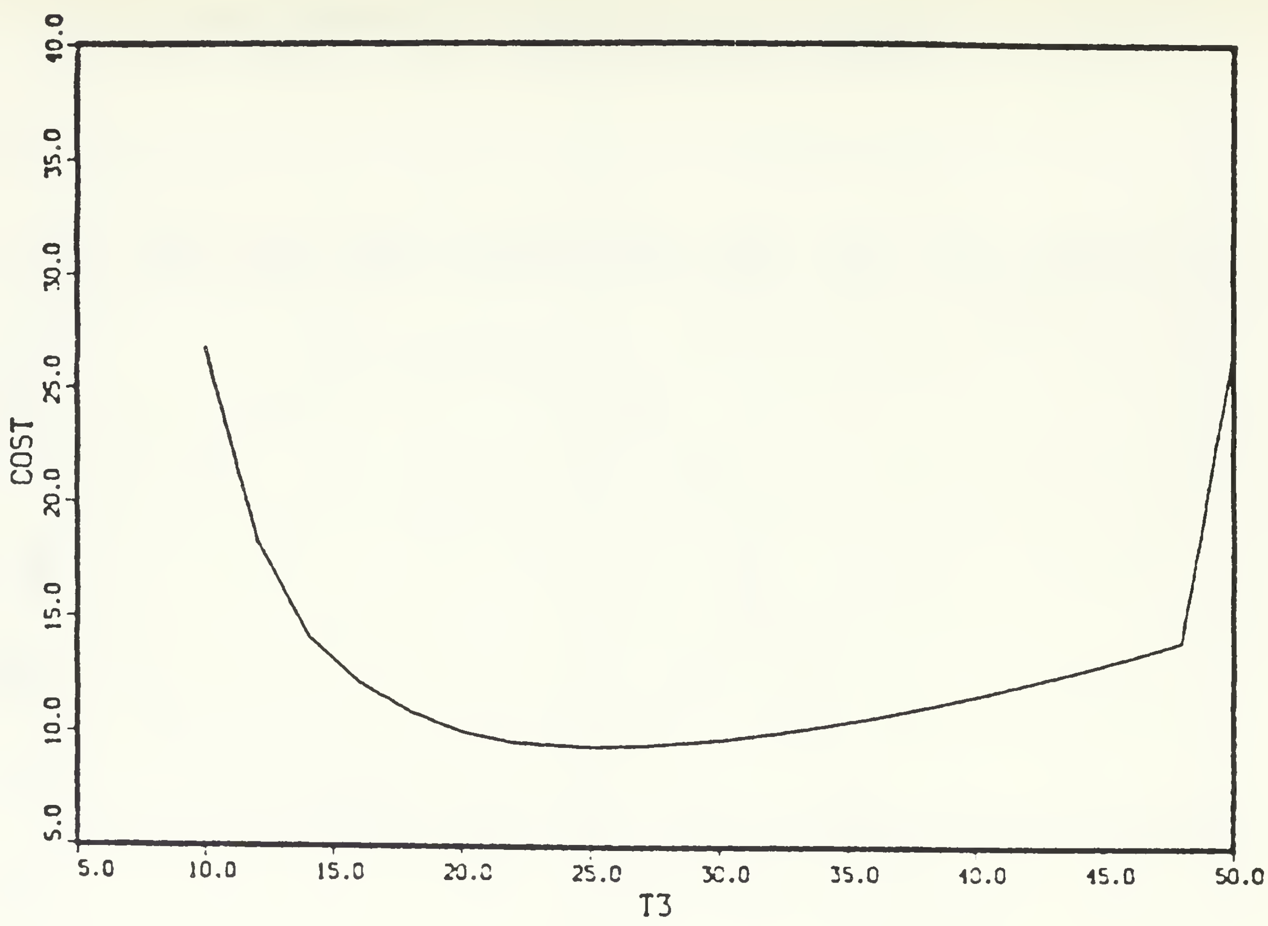

Figure 4.18 Cost Vs T3, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

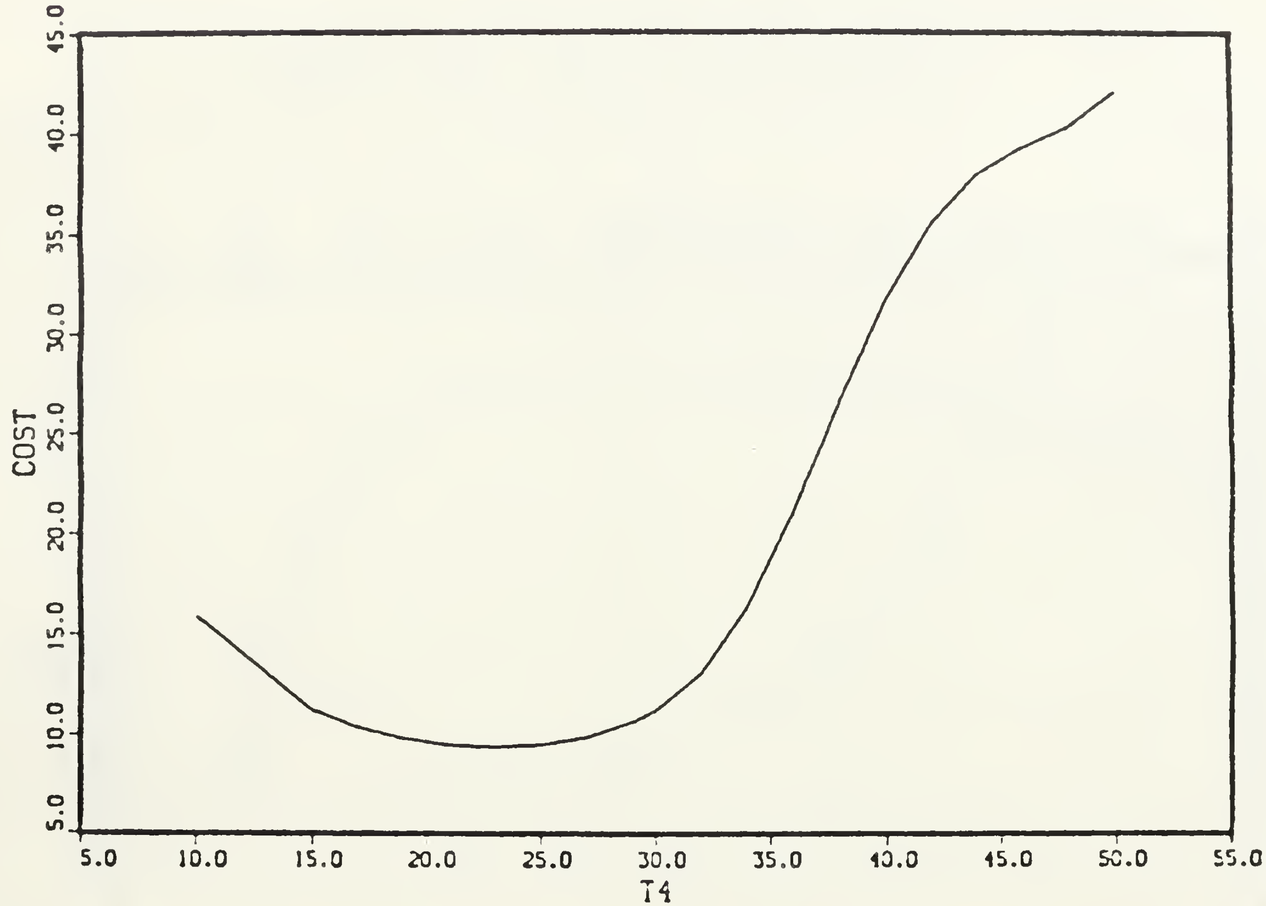

Figure 4.19 Cost Vs T4, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

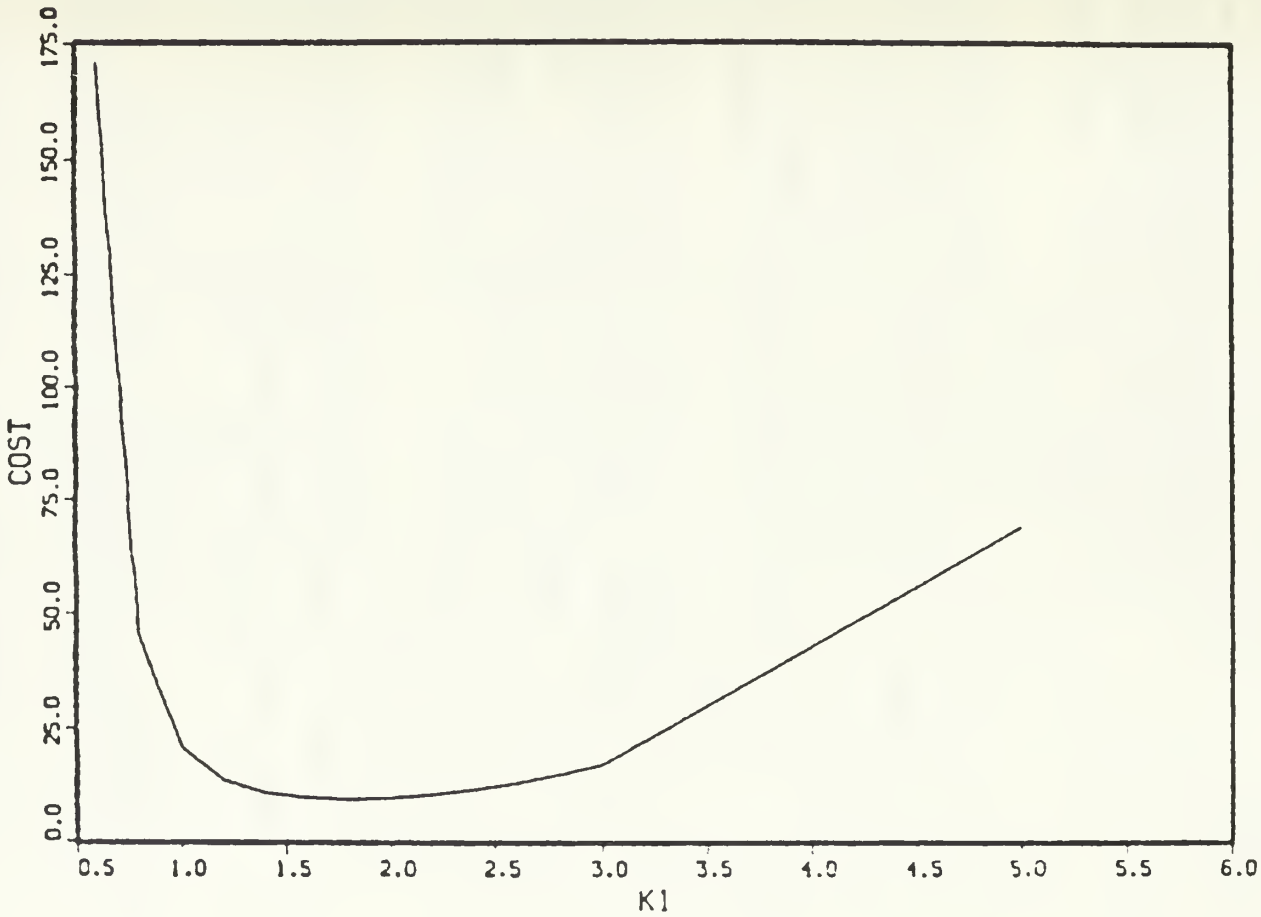

Figure 4.20 Cost Vs K1, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

V. IRREGULAR SEAS-CONTROLLER DESIGN

A sea state generator program which genarates added mass, added inertia values and in addition calculates the forces and moments,was coupled to the fortran program shown in Appendix D, so that the function minimization subroutine (BOXPLX) could be used in the presence of the irregular sea.The forces and moments were stored in a look up table which was coupled to the equation of motion.

The optimal gains obtained for 0.75 rad/sec encounter frequency in the regular sea study were used as the initial guess in order to evaluate the optimal controller parameters involving the irregular sea.

It is known that sea is never regular but actually is a random phenomenon where waves are continually changing in height, length and breadth.

Since the sea state during this study is represented by irregular waves then the waves impinding on the ship hull would contain the total energy density spectrum. This dencity specrum is composed of many frequencies and therefore the response of the ship would be to an average value of added mass and added inertia.

For this study where the ship's speed is 23 knots,the controller has the form of equation B.1, we used values for added mass and added inertia corresponding to 0.75 rad/sec because close to that frequency the energy density is maximum.

The optimal controller parameters found are shown in Table 12,and typical system's response is shown in Figures 5.1,5.2,5.3,5.4,5.5

These plots were obtained using the program of Appendix E.

A careful analysis of the extracted results leads to conclude:

- The maximum deviation of controller parameters values occured at 30° encounter angle.
- For all encounter angles the maximum cost occured for sea state 7.
- For specific encounter angles the higher the sea state the higher the cost.

TABLE 12

Controller C for Different Encounter Wave Angle

0° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	1.7460003	1.7460003	1.7460003
T1=	35.2969971	35.2969971	35.2969971
T2=	22.2480011	22.2480011	22.2480011
T3=	13.6510000	13.6510000	13.6510000
T4=	22.1170044	22.1170044	22.1170044
Cost J=	0.9438775E-34	0.3782326E-34	0.4605412E-33

30° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	2.4596768	1.5688477	2.4804857
T1=	88.2797241	47.3260040	56.3383179
T2=	50.5678864	35.6789203	51.4950714
T3=	5.2703905	21.5429993	5.7071409
T4=	95.3189392	25.0237122	91.6153102
Cost J=	0.8905333E-01	0.4461777E-01	0.1304857E+00

60° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	0.3419376	0.1919854	0.2646747
T1=	99.6322021	16.3320312	15.4308896
T2=	35.0456085	38.0289001	35.0908203
T3=	38.9945677	34.9145813	38.4357300
T4=	25.1149750	60.8223572	62.9836578
Cost J=	0.1788034E-03	0.3666982E-02	0.1193313E-01

90° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

Sea State:	4	6	7
K1=	0.5902819	2.4912267	2.4547853
T1=	87.4059400	55.7961656	32.7171021
T2=	34.5666444	35.6789999	33.8865433
T3=	39.6794654	30.2094433	4.9768888
T4=	25.1668799	25.0789005	25.3325553
Cost J=	0.7864684E-01	0.1778146E-01	0.2522047E+00

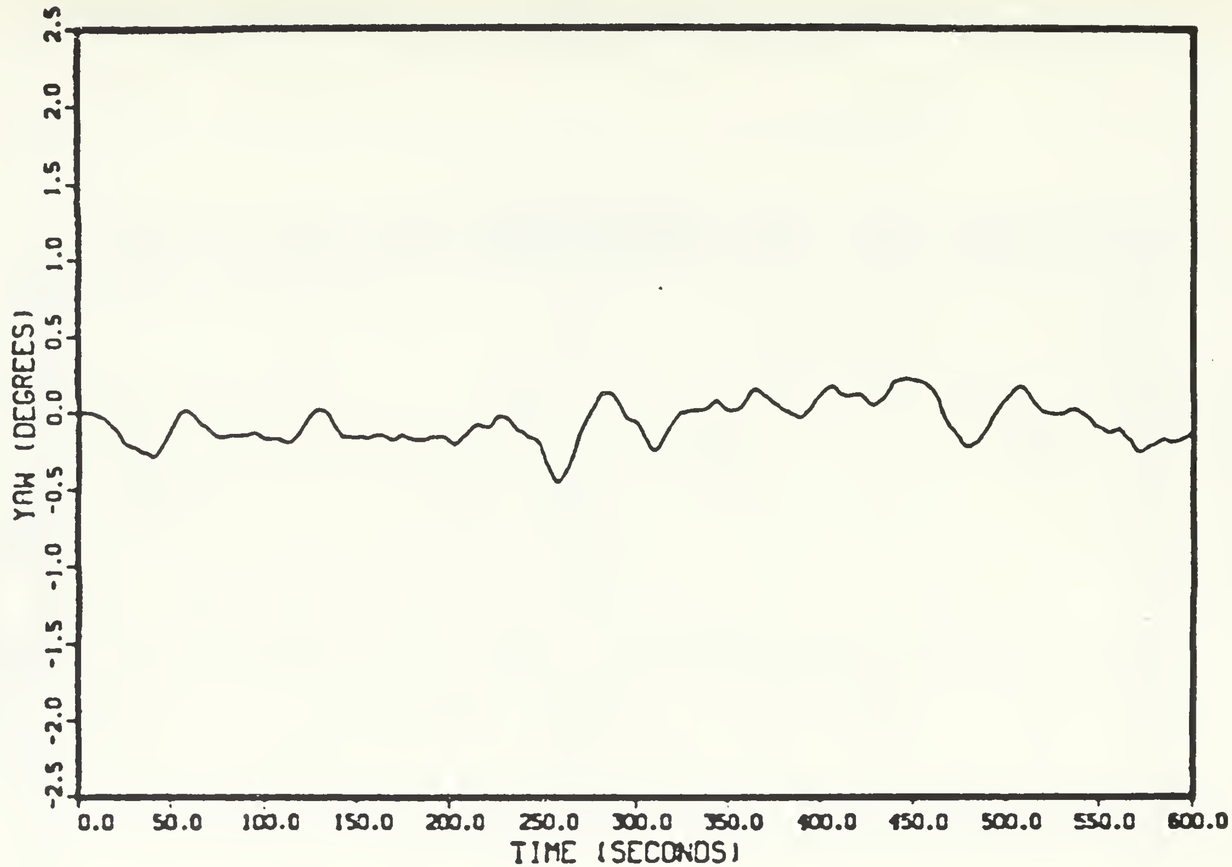

Figure 5.1 Yaw vs Time, Sea State 4.
Encounter Frequency 0.75 Rads Per Sec,Encounter Angle 30°

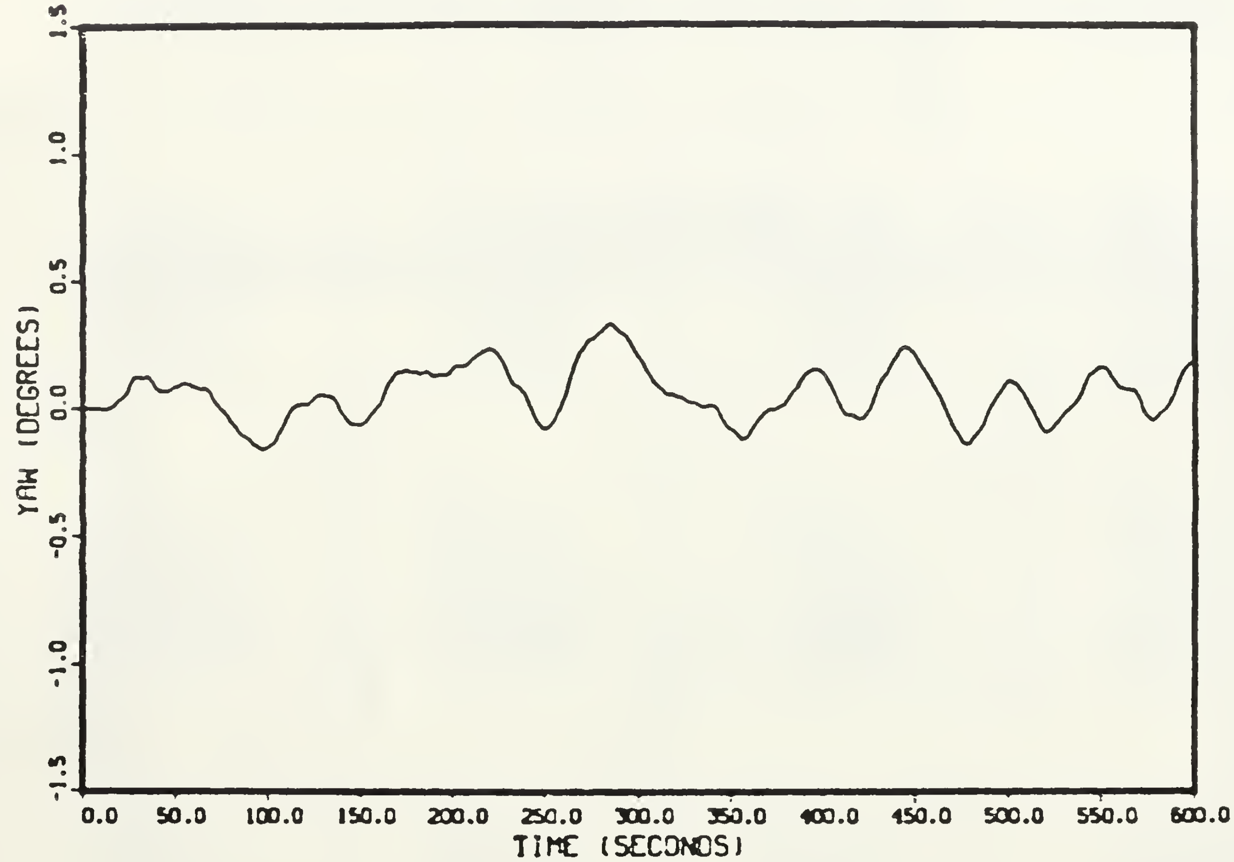

Figure 5.2 Yaw vs Time, Sea State 6.
Encounter Frequency 0.75 Rads Per sec, Encounter Angle 30°

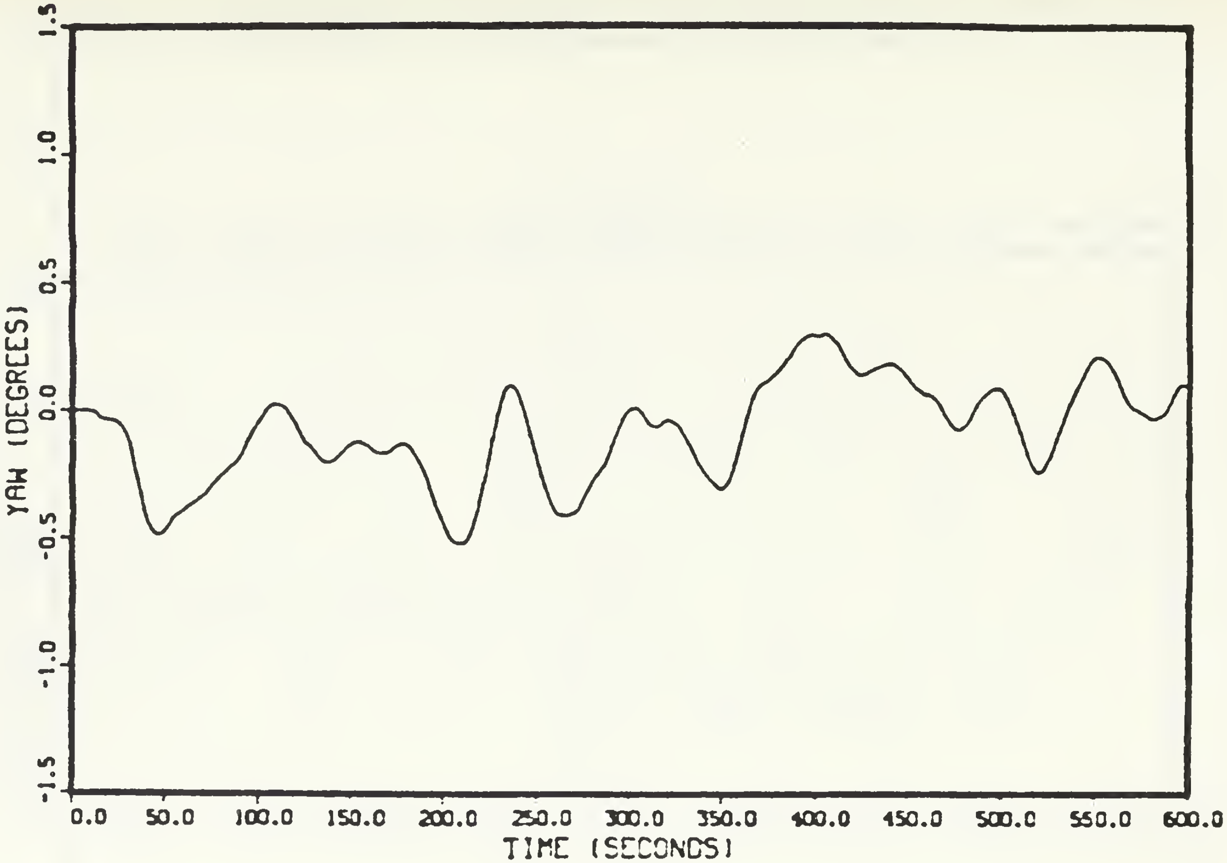

Figure 5.3 Yaw vs Time, Sea State 7.
Encounter Frequency 0.75 Rads Per Sec,Encounter Angle 30°

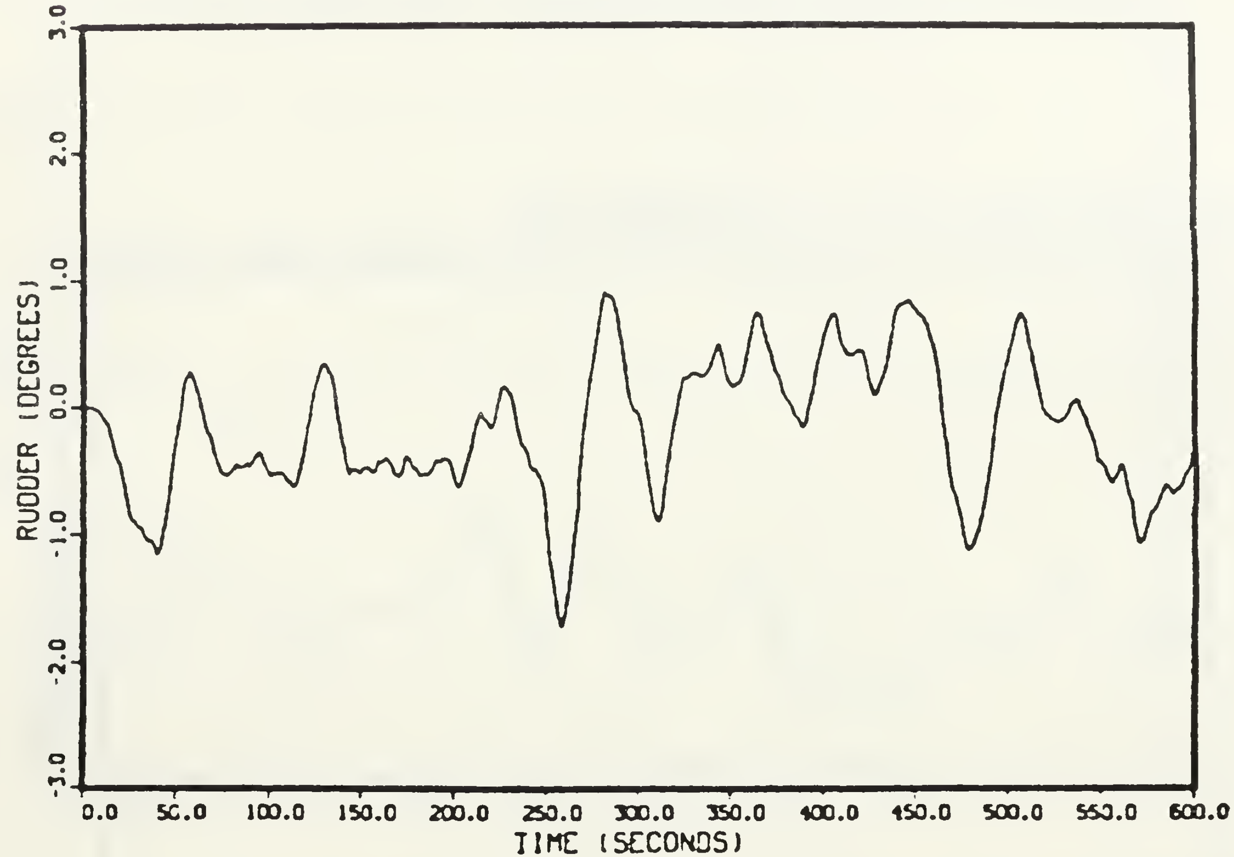

Figure 5.4 Rudder vs Time, Sea State 4.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

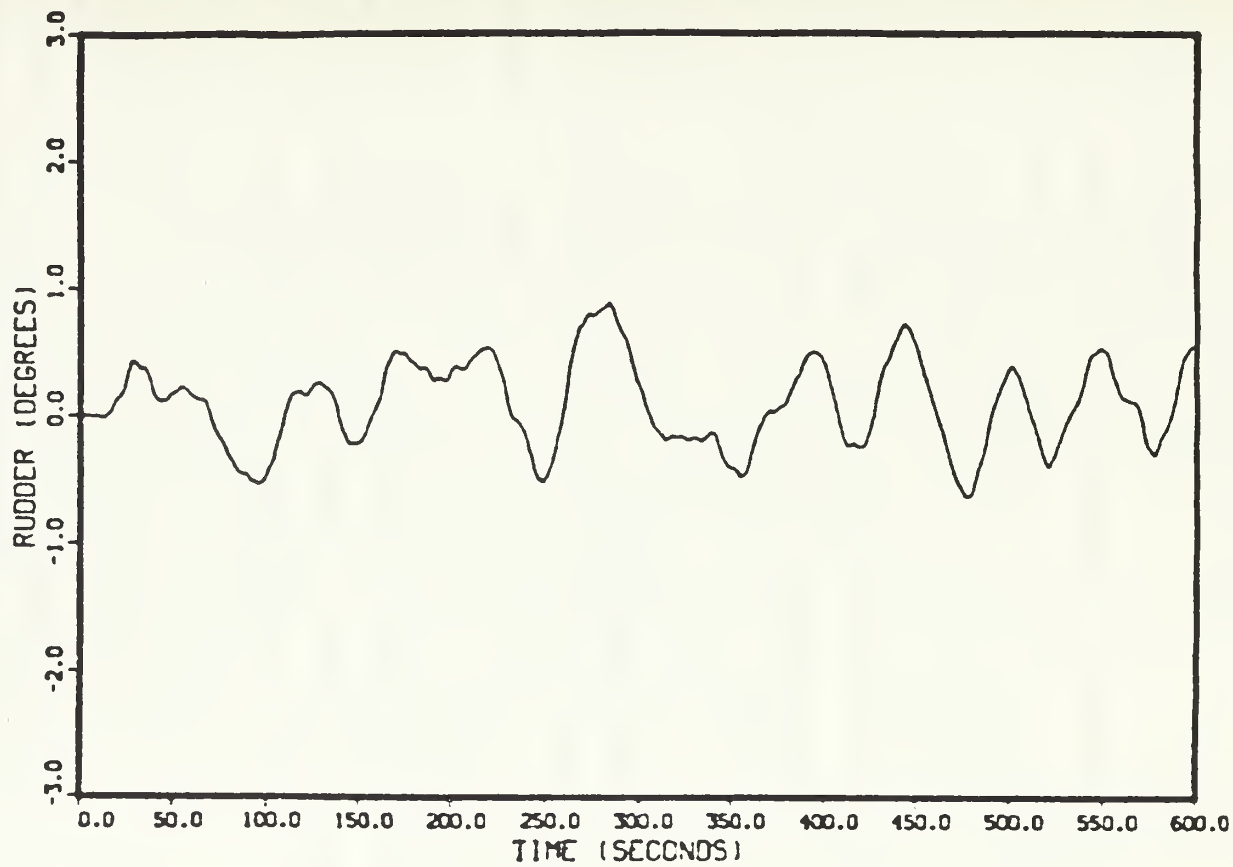

Figure 5.5 Rudder vs Time, Sea State 6.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

VI. ADAPTIVE CONTROL

A. STRUCTURE

When the ship is moving in a seaway, the controller parameters are changing due to alterations in the sea state and encounter angle. In addition we know that using fixed parameters for the controller over the entire spectrum,it is somewhat difficult to have an appropriate response of the system.The adjustment of the controller parameters during operation in a seaway,can be achieved by means of an adaptive control.

The adaptive controller can be built with digital circuits and analog components as well. Analog system hardware has to be designed for each specific requirement, and any new requirement involves changes to components. This is a time consuming task.However,for simple control requirements anolog systems still have a possible economic advantage over digital systems [Ref. 11].

On the other hand,digital systems are immediately more attractive when control systems are required to carry out more and more complex tasks.The advent of microprocessors and associated components has enabled low cost microcomputers to be built.These no longer require special environments and are fully compatible with shipboard use.The advantages of microcomputer controls over other types are that they are extremely reliable particularly as relatively fewer components are required and hence they are smaller. Their capability is greater than comparable analog systems due to their ability to carry out more complex calculations. A major advantage is their flexibility while using standard hardware, being able to be reconfigured for changes in

system requirement without the need to alter the hardware.This flexibility is achieved by the programmed software which is stored in the memory of the computer.

An adaptive control scheme is indicated in Figure 6.1 and in Figure 6.2 we show analytically the components of what we call the 'Decision Generator'.

B. SEARCH ALGORITHM

The parameters corresponding to various environmental conditions(sailing modes) are sorted in a memory.When the sailing modes change, delta(δ) and psi(ψ) vary so that the value of the performance index changes from its theoretical value. This change is detected by the threshold detector.

If the threshold is too small the adaptive structure will try new conditions when it is not necessary and in the opposite case the adaptive structure might not adapt to new sailing modes.

Using the term threshold we want to make sure that only significant changes in the environmental conditions will be considered, otherwise the system will look for a new model too often.

When the threshold detects that a new set of parameters should be used the search algorithm will look for conditions close to the previous one because the external conditions are not expected to vary rapidly. Then a new optimal value of J is selected and must be matched with the performance index computed for the real psi and delta.

Matching operation must be done after some delay ensuring that the conditions had an effect on the real cost function.

These new parameter values will be fed into the controller and function minimization subroutine as well.

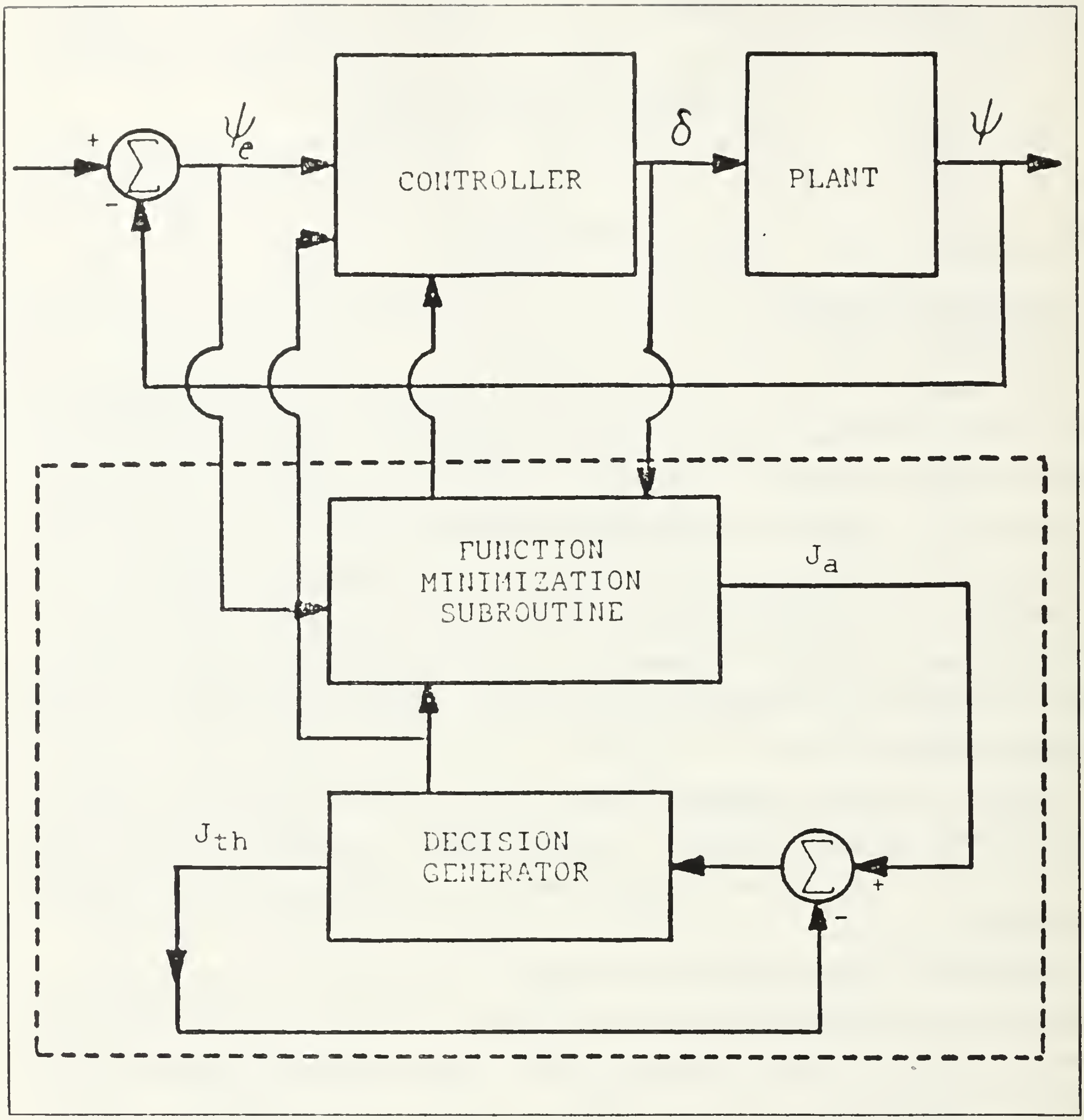

Figure 6.1 Adaptive Control Scheme

C. ADVANTAGES

- Using this adaptive scheme we don't use sensors which may be unrealistic and the use of predetermined filters which are so expensive can be avoided.

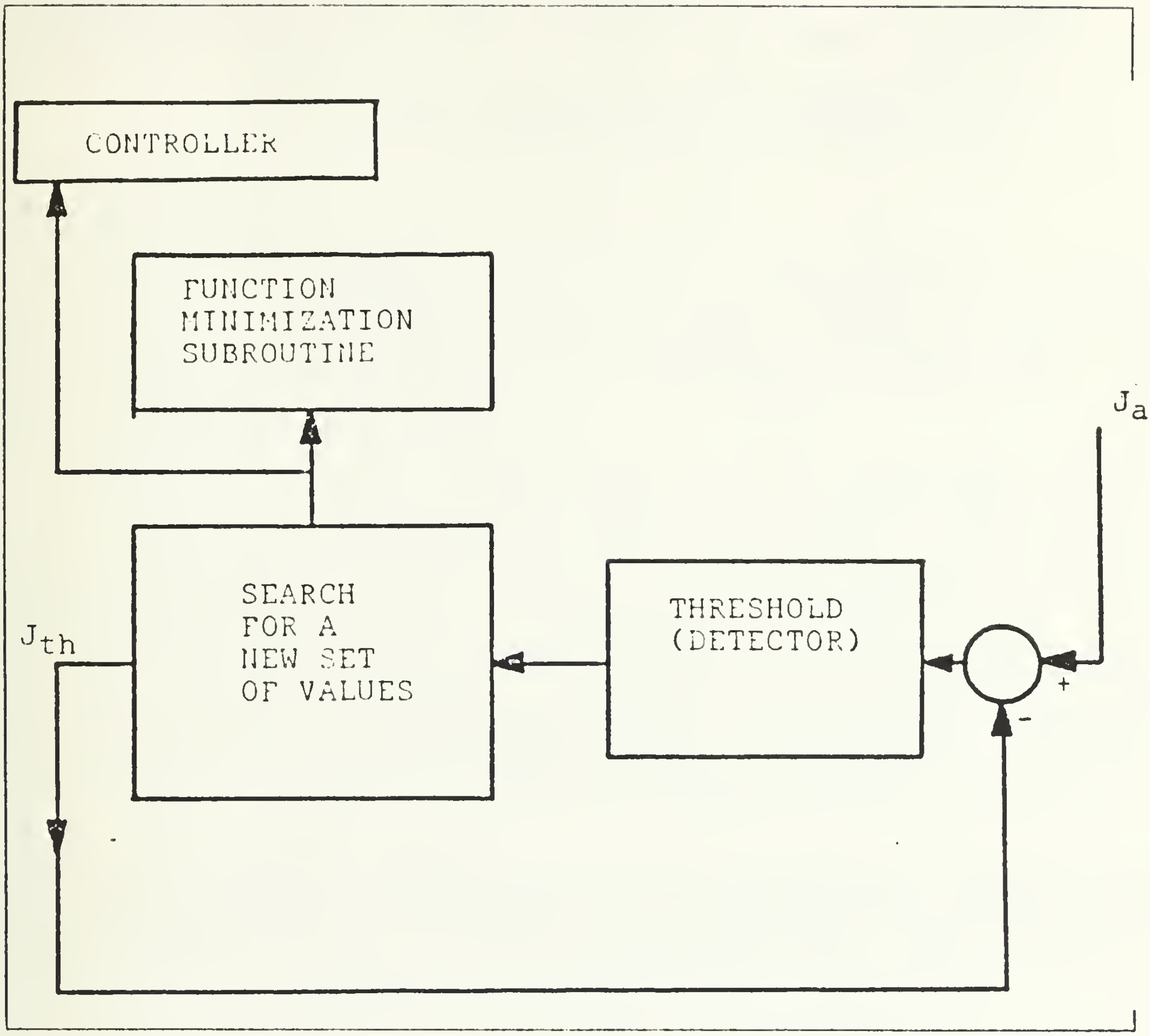

Figure 6.2 Decision Generator

- Provides a good choice for the function minimization subroutine to start it's iteration algorithm and therefore we get the optimum values as quickly as possible.

D. DISADVANTAGES

- The search algorithm must be carefully determined.
- Since we don't include sensor's measurements there is no indications on how to perform the search. This

problem can be eliminated when the NAVSTAR/GLOBAL POSITION SYSTEM (GPS) will be able to provide precision navigation data.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

- A properly designed controller can minimize the rudder activity providing desired overseas heading as well,and therefore does result in substantial improvement in propulsion efficiency.
- Actual savings in fuel cannot yet be determined since there is no information available from the conventional autopilot and therefore there is no possibility for comparison.
- It is believed that the performance index used in this research is a fairly adequate function.Doubts arise from the weighting factor which is included and this because lambda is based on assumptions and it's accuracy is not certain.
- An adaptive controller which minimizes propulsion losses due to steering is needed when environmental conditions and ship characteristics change.
- Studying all the investigated sailing modes, it turns out that the cost surface is flat.As a consequence determination of the controller parameters does not require high accuracy.
- The study shows that the use of the third order ship Nomoto model is a reasonable choice instead of using the ship's equation of motion,which involves both the sway and yaw equations.
- It can be assumed from the work done in this research that some of the findings could have applicability to a number of ship types.However it is not possible to make inference, of a general nature concerning all ships

from the results of the SL-7 which represents a particular type of a particular class of ships.

B. RECOMMENDATIONS FOR FUTURE STUDY

- Additional work has to be done for obtaining optimum controller parameters under an expanded range of operating conditions. The more optimum controller parameter values available, the better the determination of the search algorithm recommended in the adaptive control scheme.
- A study including the surge equation in our ship model is recommended since in reality added resistance due to steering reduces ship's speed and so far we assumed constant speed. In addition with the use of the surge equation we can determine actual energy losses.
- Investigation of more advanced methods of adaptive control based on "on-line" determination of plant characteristics.
- So far we were interested in minimizing rudder and yawing activity to reduce propulsion losses using a particular performance criterion in open seas.Considering some other types of control such as automatic control for replenishment requires an investigation as to the suitability of the cost function, and a comparison with other potential cost functions.

APPENDIX A

DETERMINATION OF NOMOTO THIRD ORDER MODEL-BOXPLX

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=G
//*MAIN ORG=NPGVM1.????P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C THIS PROGRAM WILL OBTAIN THE CONTROLLER OPTIMAL GAINS.
C IT IS REFERENCED IN CHAPTER 5.
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*).
         DIMENSION XS(5),XU(5),XL(5)
         XS(1)=1.7466650
         XS(2)=35.2978973
         XS(3)=22.2485657
         XS(4)=13.6511078
         XS(5)=22.1172638
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
         XL(1)=0.1
         XU(1)=4.0
         XL(2)=0.1
         XU(2)=80.0
         XL(3)=1.0
         XU(3)=50.0
         XL(4)=1.0
         XU(4)=30.0
         XL(5)=1.0
         XU(5)=50.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
       R=9./13.
```

```
      NTA=1000
      NPR=100
      NAV=0
      NV=5
      IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
      CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
      WRITE (6,25)
25    FORMAT(1X,' OPTIMAL GAINS',/)
      DO 30 I=1,5
30    WRITE(6,40)I,XS(I)
40    FORMAT(1X,'X(',I2,')=',F14.7)
      STOP
      END
      SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
     COMMON TDIFF
     REAL*8 L,L2,L3,L4,L5,L6
     REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
     REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
     REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
     REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
     REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,RXI,WA,WE
     REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
     REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR
     REAL*8 T3,T4,X3,DX3,X4
     DIMENSION XX(5)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
     ETIME=600.0
```

```
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
      T3=XX(4)
      T4=XX(5)
C     WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,'T1 =',F15.7,' T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
```

```
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
      RXR=-0.15744D+05
      RXI=-0.19950D+06
      RYR=0.52365D+04
      RYI=0.18699D+06
      MZR=-0.29870D+08
      MZI=-0.35751D+07
C     RXR=-0.50230D+04
C     RXI=0.12712D+05
C     RYR=0.35290D+04
C     RYI=-0.31909D+05
C     MZR=0.38826D+07
C     MZI=-0.64313D+07
C     RXR=0.28540D+04
C     RXI=-0.99574D+04
C     RYR=-0.85441D+04
C     RYI=0.39595D+05
C     MZR=-0.13014D+08
C     MZI=0.11348D+08
C     RXR=-0.75642D+04
C     RXI=0.83497D+04
C     RYR=0.23379D+05
C     RYI=-0.81502D+05
C     MZR=0.28622D+07
C     MZI=-0.19388D+08
```

```
C     RXR=-0.37916D+04
C     RXI=0.16381D+04
C     RYR=-0.76647D+05
C     RYI=-0.37685D+05
C     MZR=-0.83915D+07
C     MZI=-0.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN(RXI/RXR)
      TY=DATAN(RYI/RYR)
      TZ=DATAN(MZI/MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-5,2-10,3-15
C  4-17.5,5-22.5,6-27,7-35,8-42,9-60
      WA=17.5
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.2
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
c  PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
```

```
      DX2=(YAWE-X2)/T2
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C     YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE
C  CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
C  FREQUENCY =0.2
      YVDOT=-0.30908D+07
      YV=-0.81271D+04
C     YVDOT=-0.36185D+07
C     YV=-0.24757D+06
C     YVDOT=-0.32890D+07
C     YV=-0.11775D+07
```

```
C     YVDOT=-0.23038D+07
C     YV=-0.18267D+07
C     YVDOT=-0.59800D+06
C     YV=-0.13260D+07
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C     NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE
C  CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 90 , ENCOUNTER
C  FREQUENCY =0.2
      NRDOT=-0.26251D+12
      NR=-0.53637D+09
C     NRDOT=-0.20125D+12
C     NR=-0.94970D+10
C     NRDOT=-0.18671D+12
C     NR=-0.46860D+11
C     NRDOT=-0.14518D+12
C     NR=-0.87538D+11
C     NRDOT=-0.37261D+11
C     NR=-0.69856D+11
C  REGULAR WAVE SEA STATE
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
```

```
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1  +YVRR*V*R**2 +YRRR*R**3
     2  + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
     1  + NVRR*V*R**2 +NVVV*V**3
     2 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
   50 YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
C     WRITE (6,100) TIME,XP,X,XDOT,Y,YDOT
C    1  ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
  100 FORMAT(1X,'TIME=',F8.3,' SEC  XP=',F10.2,' LBF
     1 X=',F8.2,
     1' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT  YDOT='
     1 ,F8.4,' FT/SEC
     1',/,2X,' UC=',F8.4,' FT/SEC   U=',F8.4,' FT/SEC
     1 UDOT=',F10.6,
     1 ' FT/SEC**2   V=',F8.4,' FT/SEC   VDOT=',F10.6,
     1 ' FT/SEC**2'
     1 ,/,2X,'YAWC=',F8.4,' DEG  YAW='
     1   ,F15.7,' DEG   YAW RATE=',F15.7,' DEG/SEC
     1 YAW ACCEL=',F15.7,'
     1 DEG/SEC**2',/,2X,'RUDDER =',F15.7,' DEG ',/)
```

```
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C     X=X+XDOT*DELT
C     Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2,T3,T4
 500  FORMAT(' ',1X,'TOTAL=',F15.7,2X,
     1 'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7,2X,
     1 'T3=',F15.7,2X,'T4=',F15.7)
      RETURN
      END
      SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,
     1YMN,IER)
C
      DIMENSION V(50,50), FUN(50), SUM(25), CEN(25),
     1XS(NV),BU(NV),BL(NV)
```

```
C
      KV = 5
      EP = 1.E-6
      NTA = 2000
      IF (NTZ.GT.0) NTA = NTZ
      R = RZ
      IF (R.LE.0..OR.R.GE.1.) R=1./3.
      NVT = NV+NAV
C
C           TOTAL VARS, EXPLICIT PLUS IMPLICIT
      NT = 0
C           CURRENT TRIAL NO.
      NPT = 0
C     CURRENT NO. OF PERMISSIBLE TRIALS
      NTFS = 0
C     CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED
C
C     CHECK FEASIBILITY OF START POINT
C
      DO 4 I=1,NV
      VT = XS(I)
      IF (BL(I).LE.VT) GO TO 1
      II = -I
      VT = BL(I)
      GO TO 2
    1 IF (BU(I).GE.VT) GO TO 3
      II = I
      VT = BU(I)
    2 IF (NPR.GT.0) WRITE (6,49) II
    3 V(I,1) = VT
      CEN(I) = VT
      IF (IP.EQ.1) GO TO 4
      BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
      BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
    4 SUM(I) = VT
```

```
C
C
      NCE = 1
C           NUMBER OF CONSTRAINT EVALUATIONS
      I = 1
      IF (KE(V(1,1)).EQ.0) GO TO 5
      IF (NPR.LE.0) GO TO 12
      WRITE (6,50)
      GO TO 12
    5 NFE = 1
C
C   NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
      K = 2*NV
C
C   NUMBER OF DISPLACEMENTS ALLOWED.
      NLIM = 5*NV+10
C
C   NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED
c   FE TO TERMINATE.
      NCT = NLIM+NV
      ALPHA = 1.3
      FK = K
      FKM = FK-1.
      BETA = ALPHA+1.
C
C   INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
      IQR = R*1.E7
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101
C
C                    SET UP INITIAL VERTICES
      FUN(1) = FE(V(1,1))
      YMN = FUN(1)
    6 FI = 1.
      FUNOLD = FUN(1)
C
```

```
      DO 15 I=2,K
      FI = FI+1.
      LIMT = 0
    7 LIMT = LIMT+1
C
C   END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
      IF (LIMT.GE.NLIM) GO TO 11
C
      DO 8 J=1,NV
C
C   RANDOM NUMBER GENERATOR  (RANDU)
      IQR = IQR*65539
      IF (IQR.LT.0) IQR = IQR+2147483647+1
      RQX = IQR
      RQX = RQX*.4656613E-9
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
    8 CONTINUE
C
      DO 10 L=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,I)).EQ.0) GO TO 13
C
      DO 9 J=1,NV
      VT = .5*(V(J,I)+CEN(J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(J,I) = VT
    9 CONTINUE
C
   10 CONTINUE
C
   11 IF (NPR.LE.0) GO TO 12
      WRITE (6,51) I
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
   12 IER = -1
```

```
      GO TO 48
C
   13 DO 14 J=1,NV
      SUM(J) = SUM(J)+V(J,I)
   14 CEN(J) = SUM(J)/FI
C
C   TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
      NCE = NCE+1
      IF (KE(CEN).EQ.0) GO TO 60
      SUM(J) = SUM(J) -V(J,I)
      GO TO 7
   60 NFE = NFE+1
      FUN(I) = FE(V(1,I))
   15 CONTINUE
C
C   END OF LOOP SETTING OF INITIAL COMPLEX.
      IF (NPR.LE.0) GO TO 17
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C   FIND THE WORST VERTEX, THE 'J'TH.
      J = 1
C
      DO 16 I=2,K
      IF (FUN(J).GE.FUN(I)) GO TO 16
      J = I
   16 CONTINUE
C
C   BASIC LOOP.  ELIMINATE EACH WORST VERTEX
C   IN TURN. IT MUST BECOME NO LONGER WORST,NOT
C   MERELY IMPROVED.  FIND NEXT-TO-WORST VERTEX,
C   THE 'JN'TH ONE.
   17 JN = 1
      IF (J.EQ.1) JN = 2
C
      DO 18 I=1,K
```

```
      IF (I.EQ.J) GO TO 18
      IF (FUN(JN).GE.FUN(I)) GO TO 18
      JN = I
   18 CONTINUE
C
C   LIMT = NUMBER OF MOVES DURING THIS TRIAL TOWARD
C    THE CENTRIOD DUE TO FUNCTION VALUE.
      LIMT = 1
C
C   COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C
      DO 19 I=1,NV
      VT = V(I,J)
      SUM(I) = SUM(I)-VT
      CEN(I) = SUM(I)/FKM
      VT = BETA*CEN(I)-ALPHA*VT
      IF (IP.EQ.1) VT = AINT(VT+.5)
C
C   INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
   19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      NT = NT+1
C
C   CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C
   20 DO 25 N=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,J)).EQ.0) GO TO 26
C
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING
C   VERTEX THROUGH THE BEST VERTEX.
      IF (MOD(N,KV).NE.0) GO TO 22
      CALL FBV (K,FUN,M)
C
      DO 21 I=1,NV
```

```
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
   21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 24
C
C  CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.
C
   22 DO 23 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
   23 CONTINUE
C
   24 NT = NT+1
   25 CONTINUE
C
      IER = 1
C
C  CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C  OR BY OVER-REFLECTING THRU THE BEST VERTEX.
      IF (NPR.LE.0) GO TO 42
      WRITE (6,52) NT,J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GO TO 42
C
C  FEASIBLE VERTEX FOUND,EVALUATE THE OBJECTIVE FUNCTION.
   26 NFE = NFE+1
      FUNTRY = FE(V(1,J))
C
C  TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
      AFO = ABS(FUNTRY-FUNOLD)
      AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
C  ACTIVATE THE FOLLOWING TWO STATEMENTS
```

```
C   FOR DIAGNOSTICS PURPOSES ONLY.
C     WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),
C    1FUN(JN),NTFS,N
C  99 FORMAT (1X,I3,6E15.7,2I5)
      IF (AFO.GT.AMX) GO TO 27
      NTFS = NTFS+1
      IF (NTFS.LT.NCT) GO TO 28
      IER = 0
      IF (NPR.LE.0) GO TO 42
      WRITE (6,53) K
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
      GO TO 42
   27 NTFS = 0
C
C   IS THE NEW VERTEX NO LONGER WORST?
   28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
C
C   TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING
C   VERTEX THROUGH THE BEST VERTEX.
      LIMT = LIMT+1
      IF (MOD(LIMT,KV).NE.0) GO TO 30
      CALL FBV (K,FUN,M)
C
      DO 29 I=1,NV
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
   29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 32
C
   30 DO 31 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
```

```
   31 CONTINUE
C
   32 IF (LIMT.LT.NLIM) GO TO 33
C
C   CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST
C   BY DISPLACING TOWARD OVER-REFLECTING
C   THRU THE BEST VERTEX.
      IER = 2
      IF (NPR .LE. 0)  GO TO 42
      WRITE (6,52)  NT, J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GO TO 42
   33 NT = NT+1
      GO TO 20
C
C   SUCCESS:  WE HAVE A REPLACEMENT FOR VERTEX J.
   34 FUN(J) = FUNTRY
      FUNOLD = FUNTRY
      NPT = NPT+1
C
C   EVERY 100'TH PERMISSIBLE TRIAL, RECOMPUTE
C   CENTRIOD SUMMATION TO AVOID CREEPING ERROR.
      IF (MOD(NPT,100).NE.0) GO TO 37
C
      DO 36 I=1,NV
      SUM(I) = 0.
C
      DO 35 N=1,K
   35 SUM(I) = SUM(I)+V(I,N)
C
      CEN(I) = SUM(I)/FK
   36 CONTINUE
C
      LC = 0
      GO TO 39
```

```
C
   37 DO 38 I=1,NV
   38 SUM(I) = SUM(I)+V(I,J)
C
      LC = J
C
   39 IF (NPR.LE.0) GO TO 40
      IF (MOD(NPT,NPR).NE.0) GO TO 40
C
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C   HAS THE MAX. NUMBER OF TRIALS BEEN REACHED
C   WITHOUT CONVERGENCE?
C   IF NOT, GO TO NEW TRIAL.
   40 IF (NT.GE.NTA) GO TO 41
C
C   NEXT-TO-WORST VERTEX NOW BECOMES WORST.
      J = JN
      GO TO 17
   41 IER = 3
      IF (NPR.GT.0) WRITE (6,54)
C
C   COLLECTOR POINT FOR ALL ENDINGS.
C 1)  CANNOT DEVELOP FEASIBLE VERTEX.          IER = 1
C 2)  CANNOT DEVELOP A NO-LONGER-WORST VERTEX.IER = 2
C 3)  FUNCTION VALUE UNCHANGED FOR K TRIALS.  IER = 0
C 4)  LIMIT ON TRIALS REACHED.                IER = 3
C 5)  CANNOT FIND FEASIBLE VERTEX AT START.   IER = -1
   42 CONTINUE
C
C   FIND BEST VERTEX.
      CALL FBV (K,FUN,M)
      IF (IER.GE.3) GO TO 44
C
C   RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER
```

```
C   THAN THE PREVIOUS, OR IF THIS IS THE FIRST TRY.
      IF (NPR.LE.0) GO TO 43
      WRITE (6,55) (M,YMN,FUN(M))
   43 IF (FUN(M).GE.YMN) GO TO 47
      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C
C   GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
   44 YMN = FUN(M)
      FUN(1) = FUN(M)
C
      DO 45 I=1,NV
      CEN(I) = V(I,M)
      SUM(I) = V(I,M)
   45 V(I,1) = V(I,M)
C
      DO 46 I=1,NVT
   46 XS(I) = V(I,M)
C
      IF (IER.LT.3) GO TO 6
   47 IF (NPR.LE.0) GO TO 48
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
      WRITE (6,56) FUN(M)
   48 RETURN
C
   49 FORMAT (50H0INDEX AND DIRECTION OF
     1OUTLYING VARIABLE AT STARTI5)
   50 FORMAT (50H0IMPLICIT CONSTRAINT
     1VIOLATED AT START. DEAD END.)
   51 FORMAT ('0CANNOT FIND FEASIBLE',I4,'TH
     1VERTEX OR CENTROID AT START.')
   52 FORMAT (10H0AT TRIAL I4,54H CANNOT FIND
     1FEASIBLE VERTEX WHICH IS NO LONGER
     1WORST,I4,15X,'RESTART FROM BEST VERTEX.')
   53 FORMAT (40H0FUNCTION HAS BEEN ALMOST
     1UNCHANGED FOR I5,7H TRIALS)
```

```
   54 FORMAT (27H0LIMIT ON TRIALS EXCEEDED. )
   55 FORMAT ('0BEST VERTEX IS NO.',I3,'
     1 OLD MIN WAS 'E15.7',  NEW MIN IS ',E15.7)
   56 FORMAT ('0MIN OBJECTIVE FUNCTION IS ',E15.7)
      END
      SUBROUTINE FBV (K,FUN,M)
      DIMENSION FUN(50)
      M = 1
C
      DO 1 I=2,K
      IF (FUN(M).LE.FUN(I)) GO TO 1
      M = I
    1 CONTINUE
C
      RETURN
      END
      SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
      DIMENSION V(50,50), FN(50), C(25)
      WRITE (6,4) NT,NPT,NFE,NCE
C
      DO 1 I=1,K
      WRITE (6,5) FN(I),(V(J,I),J=1,NV)
      IF (NVT.LE.NV) GO TO 1
      NVP = NV+1
      WRITE (6,6) (V(J,I),J=NVP,NVT)
    1 CONTINUE
C
      IF (IK.NE.0) GO TO 2
C
      WRITE (6,7) (C(I),I=1,NV)
      RETURN
    2 IF (IK.GE.0) GO TO 3
      WRITE (6,8) (C(I),I=1,NV)
      RETURN
    3 WRITE (6,9) IK,(C(I),I=1,NV)
```

```
      RETURN
C
    4 FORMAT ('0NO. TOTAL TRIALS = ',I5,4X,
     1'NO. FEASIBLE TRIALS = ',I5,4X,'NO. FUNCTION
     1EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATI
     1ONS = ',I5/'0     FUNCTION VALUE',6X,'INDEPENDENT
     1VARIABLES/DEPENDENT OR IMPLICIT CONSTRAINTS')
    5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))
    6 FORMAT (21X,7E14.7)
    7 FORMAT (10H0CENTROID 11X,7E14.7/(21X,7E14.7))
    8 FORMAT ('0  BEST VERTEX',7X,7E14.7/(21X,7E14.7))
    9 FORMAT ('0CENTROID LESS VX',I2,2X,7E14.7/
     1(21X,7E14.7))
      END
       FUNCTION FE(X)
       DIMENSION X(5)
       COMMON TDIFF
       CALL PLANT(X)
       FE=TDIFF
       RETURN
       END
       FUNCTION KE(X)
       DIMENSION X(5)
       KE=0
       RETURN
       END
//GO.SYSIN DD *
/*
```

APPENDIX B

CONTROLLER DESIGN

A. CONTROLLER "C"

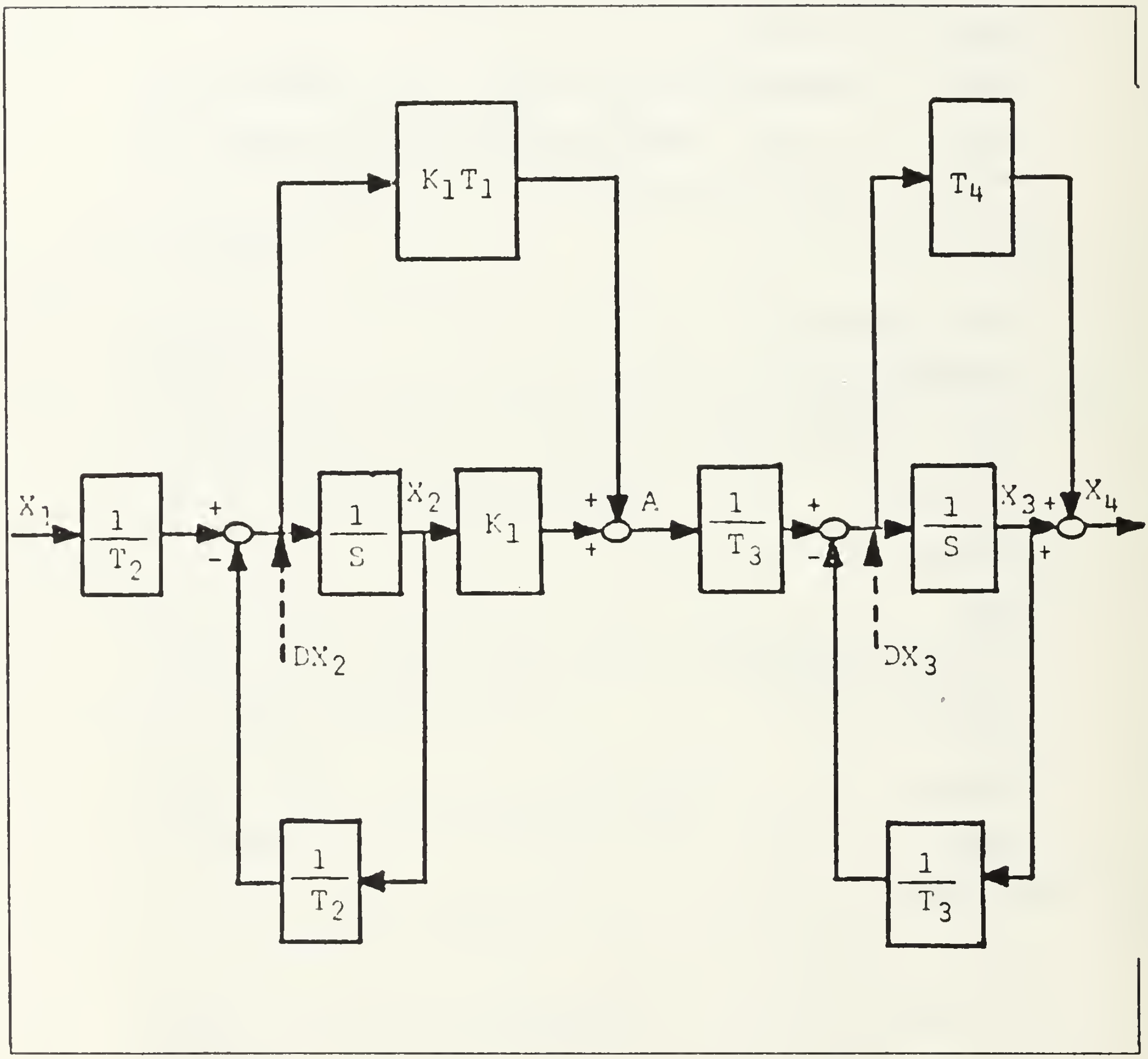

Figure B.1 Block Diagram of Controller C

Figure B.1 corresponds to controller 'C' which has the form:

$$\frac{K_1(1+T_1S)\ (1+T_4S)}{(1+T_2S)\ (1+T_3S)} \tag{B.1}$$

Verifying that equation B.1 corresponds to controller 'C' we have:

$$A=\frac{X_1K_1}{1+T_2S}+K_1T_1DX_2 \tag{B.2}$$

$$\frac{X_2}{DX_2}=\frac{1}{S} \qquad DX_2=SX_2 \tag{B.3}$$

$$\frac{X_2}{X_1}=\frac{1}{1+T_2S} \qquad X_2=\frac{X_1}{1+T_2S} \tag{B.4}$$

Substituting equations B.3 , B.4 into equation B.2 we have:

$$A=\frac{X_1K_1}{1+T_2S}+\frac{K_1T_1X_1S}{1+T_2S} \tag{B.5}$$

We also have:

$$X_4=\frac{A}{1+T_3S}+T_4DX_3 \tag{B.6}$$

$$\frac{X_3}{DX_3}=\frac{1}{S} \qquad DX_3=X_3S \tag{B.7}$$

$$\frac{X_3}{A}=\frac{1}{1+T_3S} \qquad X_3=\frac{A}{1+T_3S} \tag{B.8}$$

Substituting equations B.7 , B.8 into equation B.6 we have:

$$X_4=\frac{A}{1+T_3S}+\frac{T_4AS}{1+T_3S} \tag{B.9}$$

Now substituting equation B.5 into equation B.9 we have:

$$X =\frac{X_1K_1}{(1+T_2S)(1+T_3S)}+\frac{X_1K_1T_1S}{(1+T_2S)(1+T_3S)}+$$
$$+\frac{X_1K_1T_4S}{(1+T_2S)(1+T_3S)}+\frac{X_1K_1T_1T_4S^2}{(1+T_2S)(1+T_3S)} \tag{B.10}$$

Finally rearranging terms equation B.10 can be written:

$$\frac{X_4}{X_1}=\frac{K_1(1+T_1S+T_4S+T_1T_4S^2)}{(1+T_2S)(1+T_3S)}=\frac{K_1(1+T_1S)(1+T_4S)}{(1+T_2S)(1+T_3S)} \tag{B.11}$$

B. CONTROLLER "B"

Figure B.2 corresponds to controller 'B' which has the form:

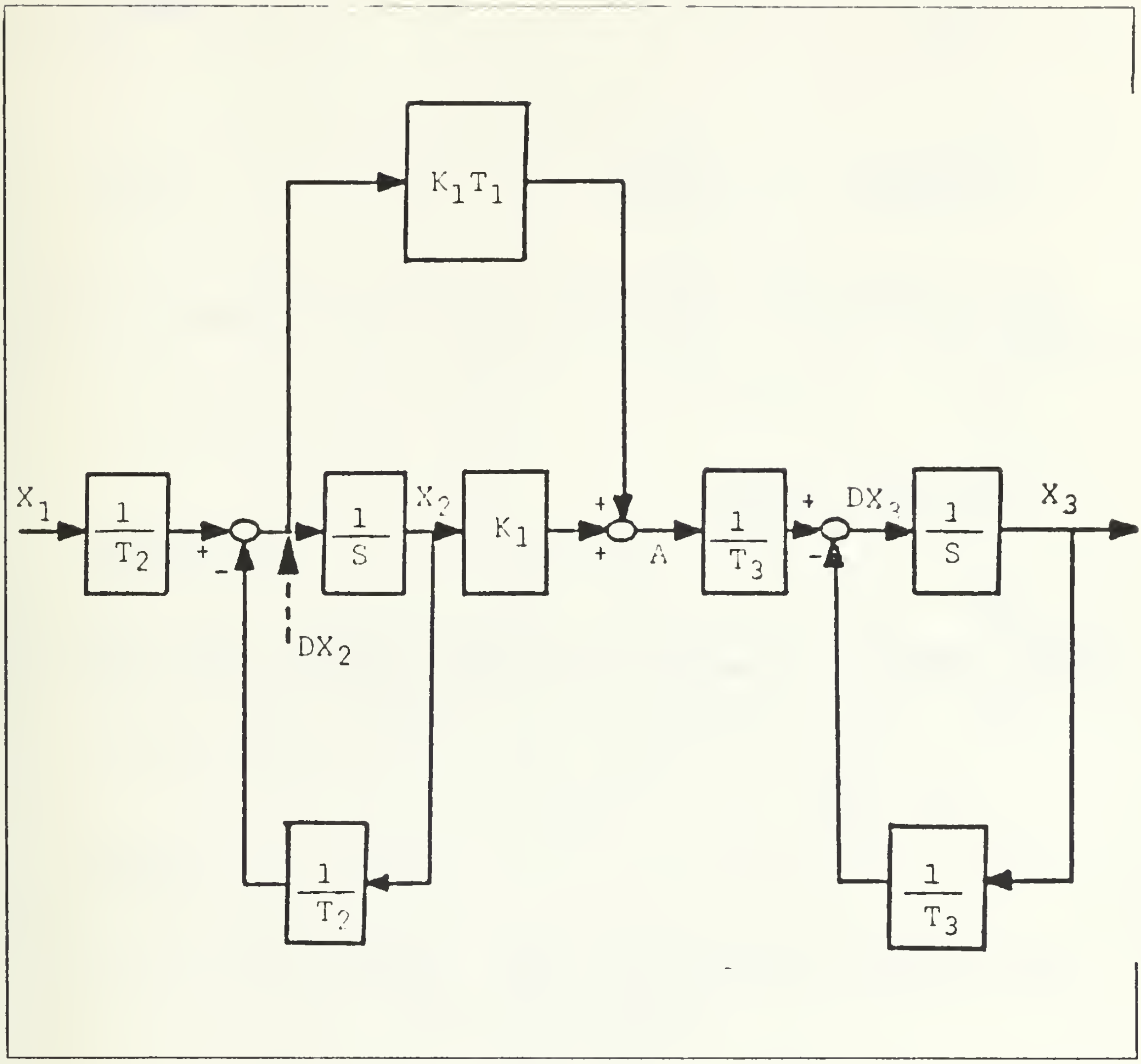

Figure B.2 Block Diagram of Controller B

$$\frac{K_1(1+T_1S)}{(1+T_2S)(1+T_3S)} \tag{B.12}$$

Verifying that equation B.12 corresponds to Controller 'B' we have:

$$A=\frac{K_1X_1}{1+T_2S} + K_1T_1DX_2 \tag{B.13}$$

$$\frac{X_2}{DX_2}=\frac{1}{S} \qquad DX_2 = X_2S \tag{B.14}$$

$$\frac{X_2}{X_1}=\frac{1}{T_2S+1} \qquad X_2=\frac{X_1}{1+T_2S} \tag{B.15}$$

Substituting equations B.14 , B.15 into equation B.13 we have:

$$A=\frac{K_1X_1}{1+T_2S}+\frac{K_1T_1X_1S}{1+T_2S} \tag{B.16}$$

In a similar way we also can derive equation B.17

$$X_3= \frac{A}{1+T_3S} \tag{B.17}$$

Substituting equation B.16 into equation B.17 we have:

$$X_3= \frac{K_1X_1}{(1+T_2S)(1+T_3S)} + \frac{K_1T_1X_1S}{(1+T_2S)(1+T_3S)} \tag{B.18}$$

Finally rearranging terms equation B.18 becomes:

$$\frac{X_3}{X_1}=\frac{K_1(1+T_1S)}{(1+T_2S)(1+T_3S)} \tag{B.19}$$

C. CONTROLLER "A"

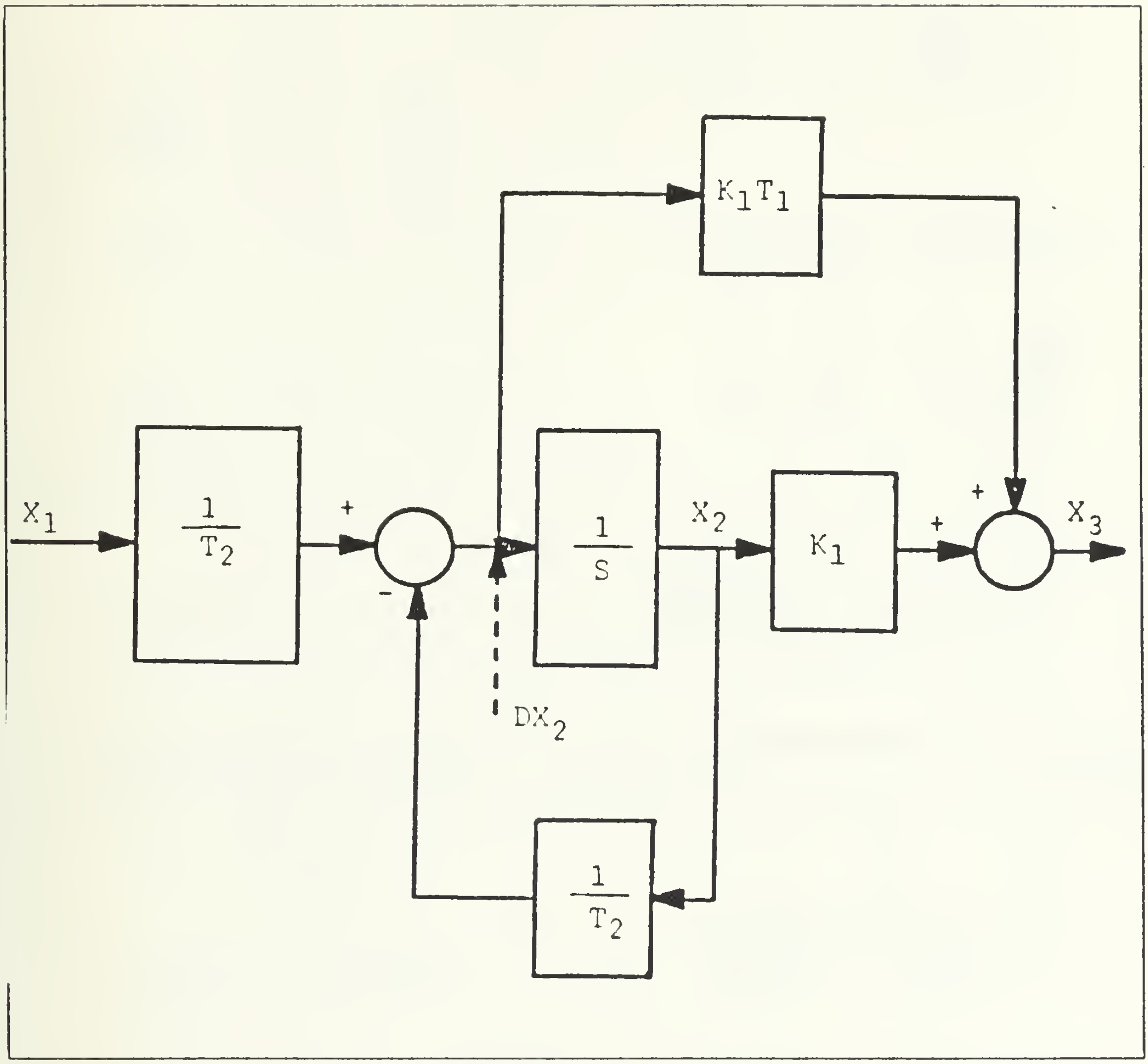

Figure B.3 Block Diagram of Controller A

Figure B.3 corresponds to controller 'A' which has the form:

$$\frac{K_1(1+T_1S)}{1+T_2S} \tag{B.20}$$

Verifying that equation B.20 corresponds to Controller 'A' we have:

$$X_3 = \frac{X_1K_1}{1+T_2S} + K_1T_1DX_2 \qquad (B.21)$$

But since we know that:

$$\frac{DX_2}{X_2} = \frac{1}{S} \qquad DX_2 = X_2S \qquad (B.22)$$

$$\frac{X_2}{X_1} = \frac{1}{1+T_2S} \qquad X_2 = \frac{X_1}{1+T_2S} \qquad (B.23)$$

Substituting equation B.22 , B.23 into equation B.21 we have:

$$X_3 = \frac{X_1K_1}{1+T_2S} + \frac{K_1T_1X_1S}{1+T_2S} \qquad (B.24)$$

Finally rearranging terms equation B.24 becomes:

$$\frac{X_3}{X_1} = \frac{K_1(1+T_1S)}{1+T_2S} \qquad (B.25)$$

D. CODING OF THE EQUATIONS

-----For Controller "C"-------------Integration--------

YAWE = YAWC - YAW

YAWE = YAW - YAWC

$$DX_2 = \frac{(YAWE - X_2)}{T_2}$$

$$A = K_1(X_2 + T_1 DX_2)$$

$$DX_3 = \frac{A - X_3}{T_3}$$

$$D = X_3 + T_4 DX_3$$

$$X_2 = X_2 + DX_2 \cdot DELT$$

$$X_3 = X_3 + DX_3 \cdot DELT$$

-----For Controller "B"-------------Integration--------

YAWE = YAW - YAWC

$$DX_2 = \frac{YAWE - X_2}{T_2}$$

$$A = K_1(X_2 + T_1 DX_2)$$

$$D = X_3$$

$$X_2 = X_2 + DX_2 \cdot DELT$$

$$X_3 = X_3 + DX_3 \cdot DELT$$

-----For Controller "A"-------------Integration--------

YAWE = YAW - YAWC

$$DX_2 = \frac{YAWE - X_2}{T_2}$$

$$D = K_1(X_2 + T_1 DX_2)$$

$$X_2 = X_2 + DX_2 \cdot DELT$$

For all of the above cases the equations include the error detector and the controller which are indicated in Figure B.4

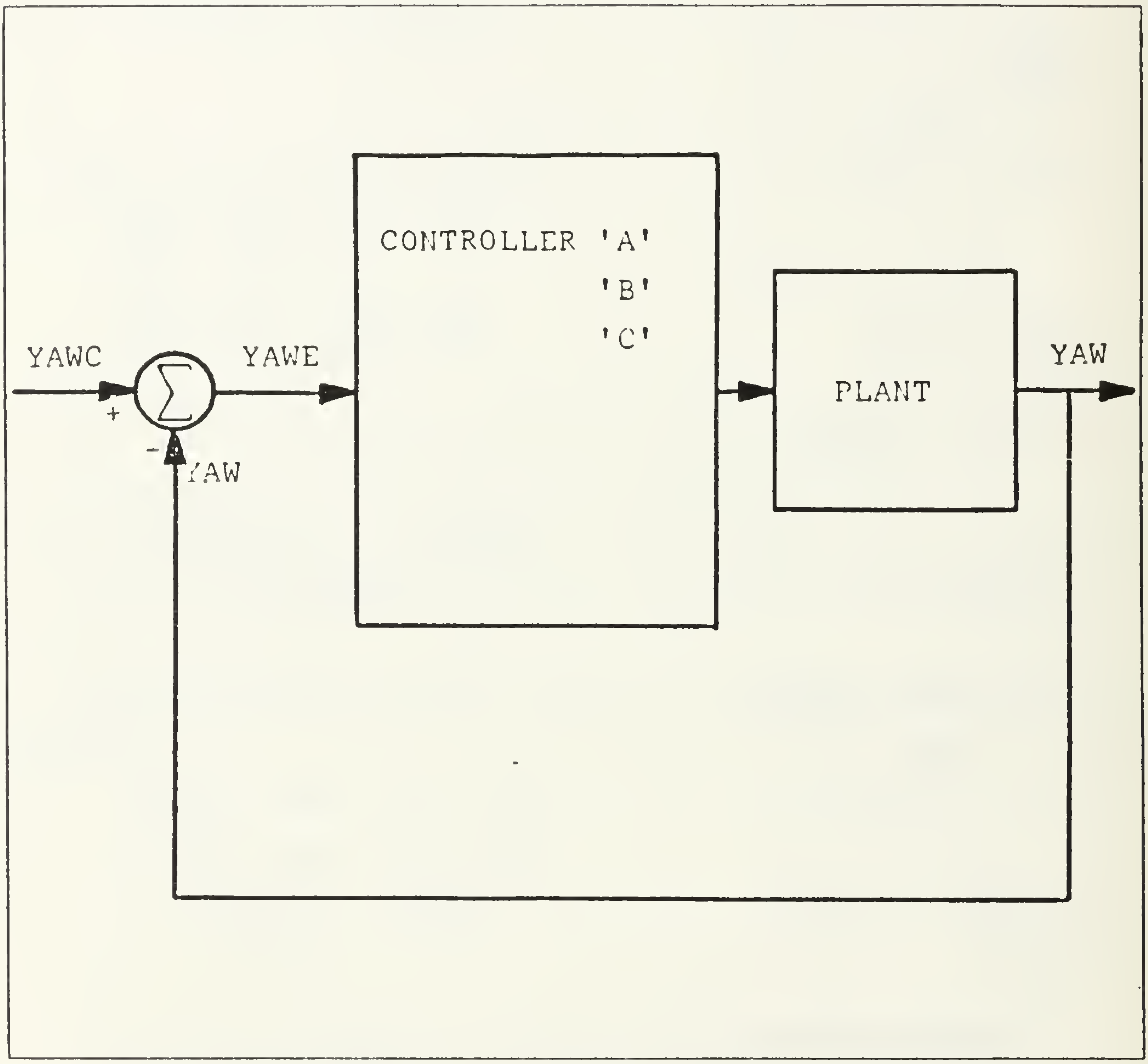

Figure B.4 General Scheme of Control

APPENDIX C

RESPONSE OF THE SYSTEM FOR REGULAR SEAS

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=A
//*MAIN ORG=NPGVM1.????P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C
C
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C HAVE BEEN OBTAINED CHANGE XS(*) TO X(*) AND DELETE
c XU(*),AND XL(*).
         COMMON J
         DIMENSION X(5)
         X(1)=1.8287125
         X(2)=1.1652012
         X(3)=10.5659571
         X(4)=11.7124157
         X(5)=20.5683947
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
       CALL PLANT(X)
       WRITE (6,25)
 25    FORMAT(1X,' OPTIMAL GAINS',/)
       DO 30 I=1,5
 30    WRITE(6,40)I,X(I)
 40    FORMAT(1X,'X(',I2,')=',F14.7)
       WRITE(6,50) J
50    FORMAT(1X,'J = ',E15.10)
       STOP
       END
       SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
```

```
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,RXI,WA,WE
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
      REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR
      REAL*8 T3,T4,X3,DX3,X4
      DIMENSION XX(5)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1.0
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
      T3=XX(4)
      T4=XX(5)
C     WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,'T1 =',F15.7,'T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
```

```
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C     RXR=-0.15744D+05
C     RXI=-0.19950D+06
C     RYR=0.52365D+04
C     RYI=0.18699D+06
C     MZR=-0.29870D+08
C     MZI=-0.35751D+07
C     RXR=-0.50230D+04
```

```
C     RXI=0.12712D+05
C     RYR=0.35290D+04
C     RYI=-0.31909D+05
C     MZR=0.38826D+07
C     MZI=-0.64313D+07
      RXR=0.28540D+04
      RXI=-0.99574D+04
      RYR=-0.85441D+04
      RYI=0.39595D+05
      MZR=-0.13014D+08
      MZI=0.11348D+08
C     RXR=-0.75642D+04
C     RXI=0.83497D+04
C     RYR=0.23379D+05
C     RYI=-0.81502D+05
C     MZR=0.28622D+07
C     MZI=-0.19388D+08
C     RXR=-0.37916D+04
C     RXI=0.16381D+04
C     RYR=-0.76647D+05
C     RYI=-0.37685D+05
C     MZR=-0.83915D+07
C     MZI=-0.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN(RXI/RXR)
      TY=DATAN(RYI/RYR)
      TZ=DATAN(MZI/MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-5,2-10,3-15,
C  4-17.5,5-22.5 6-27,7-35,8-42,9-60
      WA=17.5
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.6
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE
```

```
c  AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
      X4=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C  ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C     YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
```

```
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C   YUDOT IS THE ADDED MASS TERM WHICH MUST BE
C   CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C   ENCOUNTER FREQUENCY
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C   SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
c   FREQUENCY =0.4
C     YVDOT=-0.30908D+07
C     YV=-0.81271D+04
C     YVDOT=-0.36185D+07
C     YV=-0.24757D+06
      YVDOT=-0.32890D+07
      YV=-0.11775D+07
C     YVDOT=-0.23038D+07
C     YV=-0.18267D+07
C     YVDOT=-0.59800D+06
C     YV=-0.13260D+07
C   MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C     NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C   NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C   FREQUENCY
C     NRDOT=(-0.00027)*(.5*RHO*L5)
```

```
C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
C  FREQUENCY =0.4
C     NRDOT=-0.26251D+12
C     NR=-0.53637D+09
C     NRDOT=-0.20125D+12
C     NR=-0.94970D+10
      NRDOT=-0.18671D+12
      NR=-0.46860D+11
C     NRDOT=-0.14518D+12
C     NR=-0.87538D+11
C     NRDOT=-0.37261D+11
C     NR=-0.69856D+11
C  REGULAR WAVE SEA STATE
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D
     1 + YVVR*V**2*R + YVRR*V*R**2
     1  + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
     1  + FY )/(MASS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
     1 + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
     1 + MZ )/(iz-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ. 2) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
```

```
  50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,100) TIME,YAWDEG
C    1  ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
 100 FORMAT(1X,F12.8,1X,F12.8)
C    1' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT
C    1  YDOT=',F8.4,' FT/SEC
C    1',/,2X,' UC=',F8.4,' FT/SEC   U=',F8.4,'
C    1 FT/SEC    UDOT=',F10.6,
C    1 ' FT/SEC**2   V=',F8.4,' FT/SEC
C    1 VDOT=',F10.6,' FT/SEC**2'
C    1 ,/,2X,'YAWC=',F8.4,' DEG  YAW='
C    1   ,F15.7,' DEG   YAW RATE=',F15.7,'
C    1 DEG/SEC    YAW ACCEL='
C    1 ,F15.7,' DEG/SEC**2',/,2X,'
C    1 RUDDER =',F15.7,' DEG ')
C     WRITE (6,101) TIME,DDEG
C101  FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
```

```
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2,T3,T4
 500  FORMAT(' ',1X,'ISE=',F15.7,'  ISR=',F15.7,'
     1 TOTAL=',F15.7,2x,
     1 'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7,2X,
     1 'T3=',F15.7,2x,'T4=',F15.7)
      RETURN
      END
//GO.SYSIN DD *
/*
```

APPENDIX D

DETERMINATION OF OPTIMAL CONTROLLER PARAMETERS FOR IRREGULAR SEAS

```
//TRIAL1 JOB (1707,0356),'RESEARCH',CLASS=C
//*MAIN ORG=NPGVM1.1707P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  THIS PROGRAM WILL OBTAIN THE CONTROLLER OPTIMAL
C  GAINS. IT IS REFERENCED IN CHAPTER 5.
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C  HAVE BEEN OBTAINED CHANGE XS(*) TO X(*) AND
C  DELETE XU(*),AND XL(*).
         DIMENSION XS(5),XU(5),XL(5)
         XS(1)=0.655751
         XS(2)=80.5483
         XS(3)=10.74847
         XS(4)=12.9
         XS(5)=45.09
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
         XL(1)=0.1
         XU(1)=2.5
         XL(2)=40.0
         XU(2)=100.0
         XL(3)=0.1
         XU(3)=20.0
         XL(4)=5.0
         XU(4)=80.0
         XL(5)=60.0
         XU(5)=150.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
```

```
C  IS DISCUSSED IN BOXPLX
       R=9./13.
       NTA=1000
       NPR=100
       NAV=0
       NV=5
       IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
       CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
       WRITE (6,25)
25     FORMAT(1X,' OPTIMAL GAINS',/)
       DO 30 I=1,5
30     WRITE(6,40)I,XS(I)
40     FORMAT(1X,'X(',I2,')=',F14.7)
       STOP
       END
       SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
      REAL*8 K1,T1,T2,T3,T4,D,X2,DX2,X3,DX3,X4,CH(11),S
      DIMENSION XX(5)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
```

```
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
      T3=XX(4)
      T4=XX(5)
C     WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,'
C    1  T2=',F15.7  )
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN  FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
```

```
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C ISEA IS A SWITCH;ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
      ISEA=1
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
C  PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
      X4=0.0
  200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C  ( CONTROLLER  FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
```

```
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
C     YVDOT=(-0.0039)*(.5*RHO*L3)
C SPEED=23 KNOTS, ENCOUNTER ANGLE =    ,
C ENCOUNTER FREQUENCY =.75
      YVDOT=-2304300.0
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
```

```
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE
C  CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
C     NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE =     ,
C  ENCOUNTER FREQUENCY =.75
      NRDOT=-1.4518E+11
C  SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GO TO 35
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY TIME
 30   READ (12) CH
      FX=CH(3)
      FY=CH(4)
      MZ=CH(8)
 35   CONTINUE
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D +  FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
     1  + YVRR*V*R**2
     1  + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
     1  + FY )/(MASS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
```

```
     1  + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
     1 + MZ )/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
  50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
C     WRITE (6,100) TIME,XP,X,XDOT,Y,YDOT
C    1  ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
  100 FORMAT(1X,'TIME=',F8.3,' SEC  XP=',F10.2,' LBF
     1  X=',F8.2,
     1' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT  YDOT='
     1 ,F8.4,' FT/SEC
     1',/,2X,' UC=',F8.4,' FT/SEC   U=',F8.4,' FT/SEC
     1 UDOT=',F10.6,
     1 ' FT/SEC**2   V=',F8.4,' FT/SEC   VDOT=',F10.6,
     1 ' FT/SEC**2',/,2X,'YAWC=',F8.4,' DEG  YAW='
     1   ,F15.7,' DEG   YAW RATE=',F15.7,' DEG/SEC
     1  YAW ACCEL='
     1 ,F15.7,' DEG/SEC**2',/,2X,'RUDDER =',F15.7,'
     1 DEG ',/)
      ICOUNT=1
C  TEST IF WANT TO STOP
 300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
```

```
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C     XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C     YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C     X=X+XDOT*DELT
C     Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) TDIFF,K1,T1,T2,T3,T4
 500  FORMAT(' ',1X,'TDIFF =',F15.7,'  K1 =',F15.7,'
     1  T1 =',F15.7,2X,
     1 'T2=',F15.7,2X,'T3=',F15.7.2X,'T4=',F15.7)
      REWIND 12
      RETURN
      END
C     BETWEEN LINE 249(END) AND THE FOLLOWING LINE
C     (//GO.SYSIN DD *)WE HAVE TO INCLUDE BOXPLX.
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A213
```

APPENDIX E

RESPONSE OF THE SYSTEM FOR IRREGULAR SEAS

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=B
//*MAIN ORG=NPGVM1.????P
// EXEC FRTXCLGP,IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C  HAVE BEEN OBTAINED.
       DIMENSION XX(5)
C  OPTIMAL GAINS FOR CONTROLLER
       XX(1)=2.45967680
       XX(2)=88.2797241
       XX(3)=50.5678864
       XX(4)=5.27039050
       XX(5)=95.3189392
C  THE SUBROUTINE PLANT SIMULATES THE SL-7 CONTAINERSHIP
      CALL PLANT(XX)
      WRITE(6,25)
25    FORMAT(1X,'OPTIMAL GAINS',/)
      DO 30 I=1,5
30    WRITE(6,40)I,XX(I)
40    FORMAT(1X,'XX(',I2,')=',F14.7)
      STOP
      END
C
C  SUBROUTINE PLANT(XX)  SIMULATES THE SHIP
      SUBROUTINE PLANT(XX)
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
```

```
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
      REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
      REAL*8 K1,T1,T2,D,X2,DX2,S,CH(11),DX3,X3,X4
      DIMENSION XX(5)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=4.2
C  GAIN COEFFICIENTS
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
      T3=XX(4)
      T4=XX(5)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
```

```
      RDOT=0.0
      YAW=0.0
C  ORDERED SPEED IN  FEET/SEC
C   54.01 FT/SEC=32 KNOTS
      UC=38.81
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C  ISEA IS A SWITCH; ISEA=0(CAL WATER)ISEA=1(SEA STATE)
      ISEA=1
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
C  PARAMETERS.
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
      X4=0.0
  200 CONTINUE
```

```
      S=DSQRT(U**2 + V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C   ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X4)
C   AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C
C   XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C     XUDOT=(-.0001)*(.5*RHO*L3)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C   LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C   YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C     YVDOT=(-0.0039)*(.5*RHO*L3)
      YVDOT=-2304300.00
C   MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
```

```
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C     NRDOT=(-0.00027)*(.5*RHO*L5)
      NRDOT=-1.5096E+11
C  SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
       GO TO 35
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY TIME
 30    READ (12) CH
       FX= CH(3)
       FY= CH(4)
       MZ= CH(8)
 35    CONTINUE
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C     UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D + FX  + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*S)*R + YD*D + YVVR*V**2*R
     1  +YVRR*V*R**2
```

```
     1  + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
     1  + FY )/(MAS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
     1 + NVRR*V*R**2
     1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
     1 + MZ )/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ.2 ) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
   50 YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,100) TIME,YAWDEG
  100 FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C  TEST IF WANT TO STOP
  300 IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT
```

```
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWE**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
 400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF
 500  FORMAT('1',5X,'ISE=',F15.7,'  ISR=',F15.7,'
     1 TOTAL=',F15.7)
      STOP
      END
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A211
```

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5.	Professor Alex Gerba Jr., Code 62Gz Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943	1
6.	Department Chairman, Code 62Rr Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943	1
7.	LT. Kyritsis-Spyromilios Pericles H.N. Sarantaporou 125, Papagou Athens,Greece	8
8.	LT. Horianopoulos Emmanuel H.N. Travlantoni 39, Patisia Athens , Greece	1
9.	LT. Horianopoulos George H.N. Panourgia 4, Piraeus Piraeus , Greece	1
10.	Mr George Curry Henschel 9 Hoyt Drive, P.O BOX 30 Newburyport,Massachusetts 01950.	1
11.	Mr John Carter Henschel 9 Hoyt Drive, P.O BOX 30 Newburyport,Massachusetts 01950.	1

12. Mr Petros Lemonidis 1
Peloponnisou 4,
Pefki,Athens,Greece

13. Dr. Robert E. Reid 1
University of Illinois
144 Mechanical Engineering Building
1206 West Green Street
Urbuna, Illinois 61801

14. LT. Garcia Vicente, USN 1
P.O. BOX 985
Antony, New Mexico 88021

15. Tayfun Tansan 1
Goztepe Istasyon Cad. No:31/13
Istanbul, Turkey

Thesis
S66892 Spyromilios
c.1 Development of criteria for automatic steering.